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IS 7365 (2010): Criteria for hydraulic design of bucket type energy dissipators [WRD 9: Dams and Spillways]



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भारतीय मानक
बाल्टी टाइप उर्जा क्षयकारकों की द्रवचालित
डिजाइन के मापदण्ड
(दूसरा पुनरीक्षण)

Indian Standard
CRITERIA FOR HYDRAULIC DESIGN OF BUCKET TYPE
ENERGY DISSIPATORS
(*Second Revision*)

ICS 93.16

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BUREAU OF INDIAN STANDARDS
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NEW DELHI 110002

FOREWORD

This Indian Standard (Second Revision) was adopted by the Bureau of Indian Standards, after the draft finalized by the Dams and Spillways Sectional Committee had been approved by the Water Resources Division Council.

This standard was first published in 1974. The first revision was taken up in 1985 to reflect the latest practices prevailing and to utilize the knowledge gained during the use of the standard. This revision has been taken up to utilize the experience further gained during the use of this standard.

Energy dissipator at the toe of spillway of a hydraulic structure is necessary to minimize erosion of strata downstream of the structure. For this purpose there are different types of energy dissipators, such as hydraulic jump, impact, jet diffusion, interacting jets, hollow jet and multiple ski-jump. Generally bucket type energy dissipators are being used for energy dissipation in medium and high dams.

Hydraulic behaviour of bucket type energy dissipator depends on dissipation of energy through:

- a) interaction of two rollers formed, one in the bucket, rolling anti-clockwise (if the flow is from the left to the right) and the other downstream of the bucket, rolling clockwise; or
- b) interaction of the jet of water, shooting out from the bucket lip, with the surrounding air and its impact on the channel bed downstream.

Bucket type energy dissipators can be either:

- a) roller bucket type energy dissipator, or
- b) trajectory bucket type energy dissipator.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated expressing the result of a test or analysis, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

Indian Standard

CRITERIA FOR HYDRAULIC DESIGN OF BUCKET TYPE ENERGY DISSIPATORS

(Second Revision)

1 SCOPE

This standard lays down criteria for hydraulic design of bucket type energy dissipators.

2 TERMINOLOGY

For the purpose of this standard the following definitions shall apply.

2.1 Solid Roller Bucket — An upturn solid bucket (*see* Fig. 1A) is used when the tailwater depth is much in excess of sequent depth and in which dissipation of considerable portion of energy occurs as a result of formation of two complementary elliptical rollers, one in bucket proper, called a surface roller, which is anti-clockwise (if the flow is from the left to the right) and the other downstream of the bucket, called the ground roller, which is clockwise.

2.2 Slotted Roller Bucket — An upturn bucket with teeth in it (*see* Fig. 1B) is used when the tailwater depth is much in excess of sequent depth and in which the dissipation of energy occurs by lateral spreading of jet passing through bucket slots in addition to the formation of two complementary rollers as in the solid bucket.

2.3 Trajectory Bucket/Flip Bucket — An upturn solid bucket (*see* Fig. 1C) is used when the tailwater depth is insufficient for the formation of the hydraulic jump, the bed of the river channel downstream comprises sound rock and is capable of withstanding, without excessive scour, the impact of the high velocity jet. The flow coming down the spillway is thrown away from toe of the dam to a considerable distance downstream as a free discharging upturned jet which falls into the channel directly, thereby avoiding excessive scour immediately downstream of the spillway. There is hardly any energy dissipation within the bucket itself. The device is used mainly to increase the distance from the structure to the place where high velocity jet hits the channel bed, thus avoiding the danger of excessive scour immediately downstream of the spillway. Due to the throw of the jet in the shape of a trajectory, energy dissipation takes place by:

a) internal friction within the jet,

- b) interaction between the jet and surrounding air,
- c) diffusion of the jet in the tailwater,
- d) impact of the channel bed, and
- e) pre-formed plunge pool.

3 SYMBOLS

The symbols used in the standard are defined as given below:

a = vertical distance from the lip level to the highest point of the centre of jet, in m;

d_c = critical depth, in m;

d_s = depth of scour below tailwater level, in m;

D_s = horizontal distance from spillway crest axis to the point of maximum probable scour, in m;

d_1 = depth of flow entering bucket, in m;

d_2 = sequent depth, in m;

d_3 = height of tailwater above bucket invert, in m;

d_4 = tailwater level minus bucket lip elevation, in m;

F_j = Froude number of jet entering bucket;

$$= \frac{v_a}{\sqrt{gd_1}}$$

F_D = discharge parameter;

$$= \frac{q}{\sqrt{gH_1^{3/2}}} \times 10^3$$

g = acceleration due to gravity, in m/s²;

h_b = height of roller above bucket invert, in m;

h_s = height of surge above bucket invert, in m;

H = depth of overflow over spillway, in m;

H_1 = reservoir pool elevation minus bucket invert elevation, in m;

H_2 = spillway crest elevation minus bucket invert elevation, in m;

H_3 = reservoir pool elevation minus tailwater elevation, in m;

H_4 = reservoir pool elevation minus bucket lip elevation, in m;

H_5 = reservoir pool elevation minus jet surface elevation on bucket, in m;
 H_v = velocity head of jet at bucket lip, in m;
 P = pressure on the bucket, in t/m^2 ;
 q = discharge intensity per metre of bucket width, in $[m^3/s]/m$;
 Q = total discharge, in m^3/s ;
 R = radius of bucket, in m;

S_d = horizontal distance from spillway crest axis of the point of maximum probable surge, in m;
 T_{Max} = maximum tailwater depth, above bucket invert, for good performance of slotted roller bucket, in m;
 T_{Min} = minimum tailwater depth, above bucket invert, for good performance of slotted roller bucket, in m;

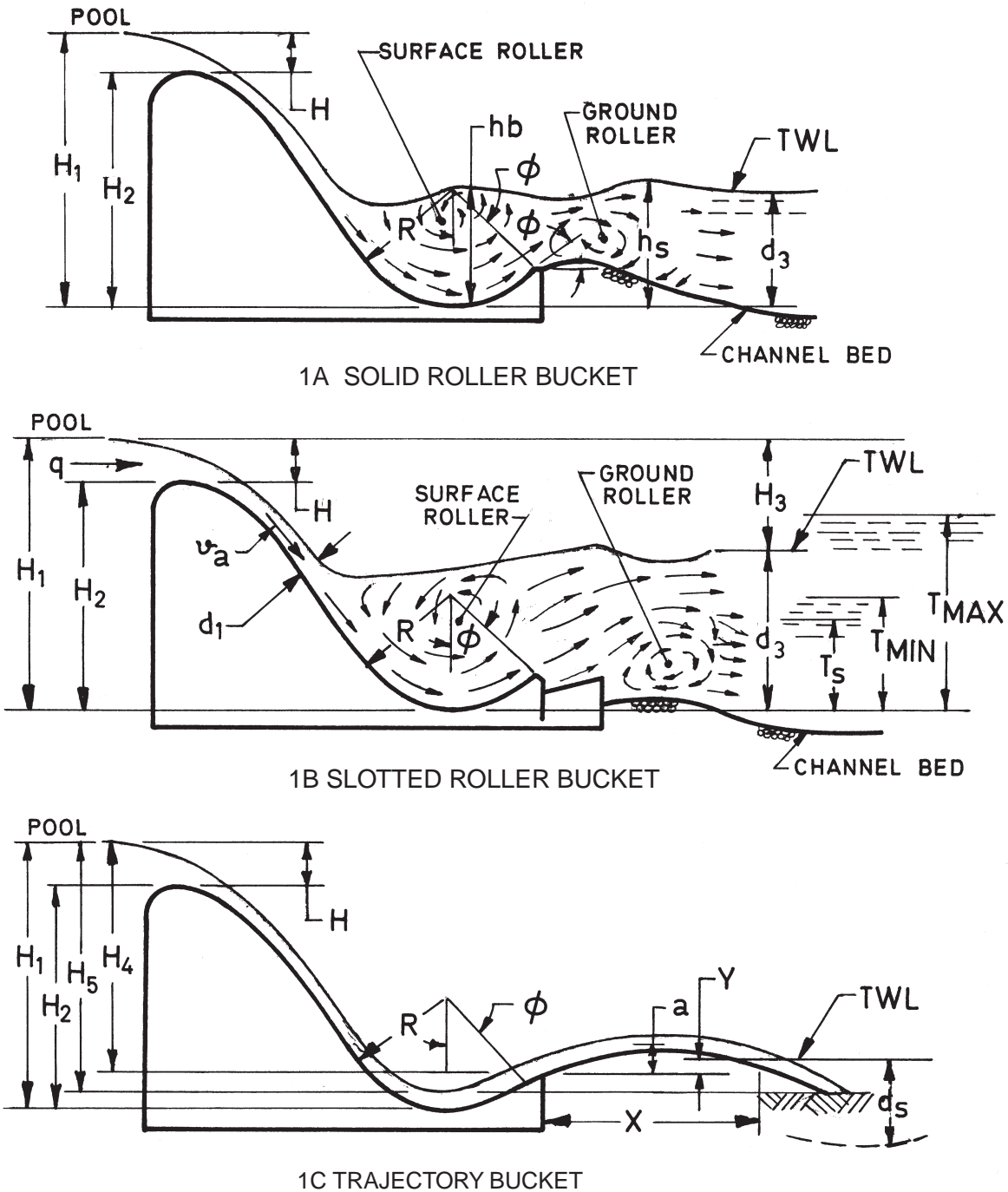


FIG. 1 SKETCHES FOR BUCKET TYPE ENERGY DISSIPATORS

- T_s = tailwater sweep out depth, in m;
 v_a = actual velocity of flow entering bucket, in m/s;
 v_t = theoretical velocity of flow entering bucket, in m/s;
 X = horizontal throw distance from bucket lip to the centre point of impact with tailwater, in m;
 Y = difference between the lip level and tailwater, sign taken as positive for tailwater below the lip level and negative for tailwater above the lip level, in m;
 γ = specific weight of water, in t/m³; and
 ϕ = bucket lip angle (exit angle) with horizontal, in degree.

4 HYDRAULIC DESIGN OF ROLLER BUCKET TYPE ENERGY DISSIPATORS (SOLID AND SLOTTED ROLLER BUCKETS)

4.1 General

4.1.1 The following two types of roller buckets are adopted on the basis of tailwater conditions and importance of the structure:

- Solid roller bucket, and
- Slotted roller bucket.

Roller bucket type energy dissipator is preferred when;

- tailwater depth is high (greater than 1.1 times sequent depth preferably 1.2 times sequent depth), and
- river bed rock is sound.

4.1.1.1 In the case of solid roller bucket, the ground roller is more pronounced. It picks up material from downstream bed and carries it towards the bucket where it is partly deposited and partly carried away downstream by the residual jet from the lip. The deposition in roller bucket is more likely when the spillway spans are not operated equally, setting up horizontal eddies downstream of the bucket. The picked up material which is drawn into the bucket can cause abrasive damage to the bucket by churning action.

4.1.1.2 In the case of slotted roller bucket, a part of the flow passes through the slots, spreads laterally and is lifted away from the channel bottom by a short apron at the downstream end of the bucket. Thus the flow is dispersed and distributed over a greater area resulting in a less violent ground roller. The height of boil is also reduced in case of slotted roller bucket. The slotted bucket provides a self-cleaning action to reduce abrasion in the bucket.

4.1.1.3 In general the slotted roller bucket is an improvement over the solid roller bucket for the range of tailwater depths under which it can operate without sweep out or diving. However, it is necessary that specific model experiments should be conducted to verify pressure on the teeth so as to avoid cavitation conditions. In case of hydraulic structures, slotted roller buckets should not be provided where heavy sediment/gravel/boulder are expected. Heavy sediment load/gravel/boulders rolling down the spillway face can cause heavy damage to the teeth thereby making them ineffective and on the contrary, increasing the chances of damage by impact, cavitation and erosion.

4.1.2 Drawal of Bed Materials

A major problem with the solid roller bucket would be the damage caused to the bucket due to churning action, because of the downstream bed material brought into the bucket by the pronounced ground roller. Even in a slotted roller bucket, downstream material might get drawn due to unequal operation of gates. The channel bed immediately downstream of the bucket shall be set at 1 to 1.5 m below the lip level to minimize the possibility of this condition. Where the invert of the bucket is required to be set below the channel general bed level, the channel should be dressed down in one level to about 1 to 1.5 m below the lip level for about 15 m length downstream and then a recovery slope of about 3 (horizontal) to 1 (vertical) should be given to meet the general bed level as shown in Fig. 2. Model studies should be done to check this tendency. If possible, even provision of properly anchored solid concrete apron laid on fresh rock may be considered to avoid river bed material drawing into the bucket, as

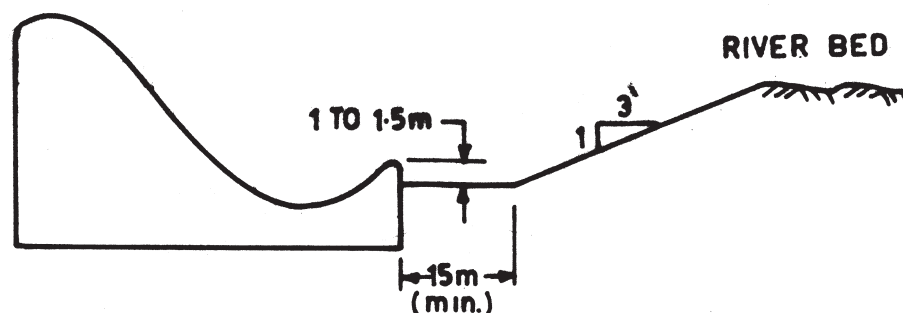


FIG. 2 RECOVERY SLOPE DOWNSTREAM OF SOLID ROLLER BUCKET

it may cause heavy erosion on the spillway face, bucket and side training walls.

4.1.2.1 In the case where the bucket invert is substantially higher than the general channel bed level and the channel bed is erodible, the cascading flow over the lip for small discharges may cause deep scour very close to the bucket lip. A concrete apron of width 15 m or more if required may be provided downstream and parallel to the end sill as shown in Fig. 3 to minimize the possible scour in the bed near the bucket lip. The apron should be keyed into good rock.

4.1.3 Precautions in Operation

It is necessary to operate all the spillways gates equally (under partial operation condition) to achieve satisfactory performance of the bucket. Unsymmetrical operation of gates or operation of only a few gates at a time may set up horizontal eddies in the channel downstream which may bring debris into the bucket. All loose debris inside and just beyond the bucket should be removed after construction and before the bucket is put to use.

4.1.3.1 Divide walls would be necessary to segregate the spillway spans, if unequal spillway operations cannot be avoided with due consideration for building of tailwater level for various discharges. Also when the invert levels of the buckets in adjacent bays are provided at different elevations, divide walls may be required depending upon the flow conditions. Model studies may be conducted for such cases. The divide walls shall be designed for unequal operation condition of the spillway spans and also for differential pressure due to adjoining gates closed on one side and all gates open on the other side.

4.2 Hydraulic Design of Solid Roller Bucket

4.2.1 General

For effective energy dissipation in a solid roller bucket both the surface or dissipating roller and the ground or stabilizing roller should be well formed, otherwise

hydraulic phenomenon of sweep out or heavy submergence occurs depending upon which of the rollers is inhibited.

4.2.2 Design Criteria

The principal features of hydraulic design of solid roller bucket consists of determining;

- bucket invert elevation,
- radius of the bucket, and
- slope of the bucket lip or the bucket lip angle.

4.2.2.1 Bucket invert elevation

Normally the invert level of a roller bucket is so fixed that the difference in the maximum tailwater level corresponding to design flood and the invert level (d_3) is between 1.1 to 1.4 times the sequent depth (d_2). Thus $d_3 = 1.1$ to 1.4 times d_2 . The design charts given in Fig. 4 and Fig. 5 and sample calculations given in Annex A may be used to determine the bucket invert elevation and probable roller and surge height for the expected range of spillway discharges. Satisfactory energy dissipation is obtained when the roller height (h_b) is between 75 and 90 percent of the tailwater depth (d_3). If the aforesaid two criteria are satisfied, then the surge height (h_s) measured above the invert level is 105 to 130 percent of the tailwater d_3 , that is, $h_s/d_3 = 1.05$ to 1.3 . When the invert elevation arrived at to get the h_b/d_3 ratio between 0.75 and 0.90, is considerably below the channel bed level, substantial excavation would be involved for dressing downstream channel bed down to 1.0 to 1.5 m below the endsill level in minimum 15.0 m length or more in the downstream depending upon the discharge intensity and the head. It would, therefore, be preferable if the invert level can be brought near to the channel bed level with the h_b/d_3 ratio still remaining within the prescribed limits, and d_3 being about 1.2 to 1.4 times d_2 . The charts are applicable for the ranges of variables shown in Fig. 4 and Fig. 5. The channel bed elevation is believed to have negligible effect on roller and surge heights.

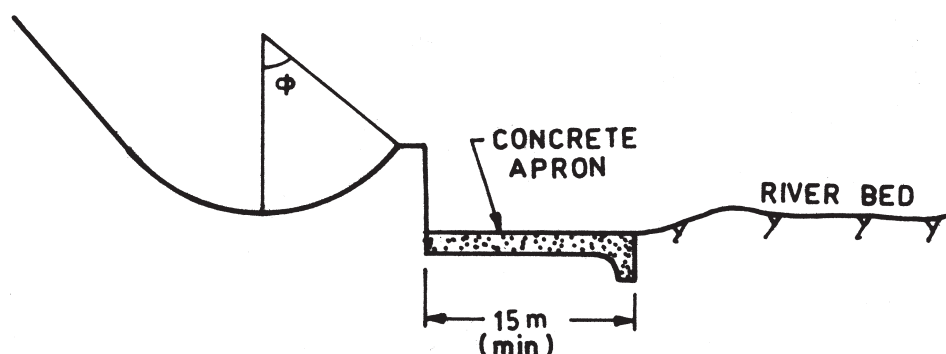
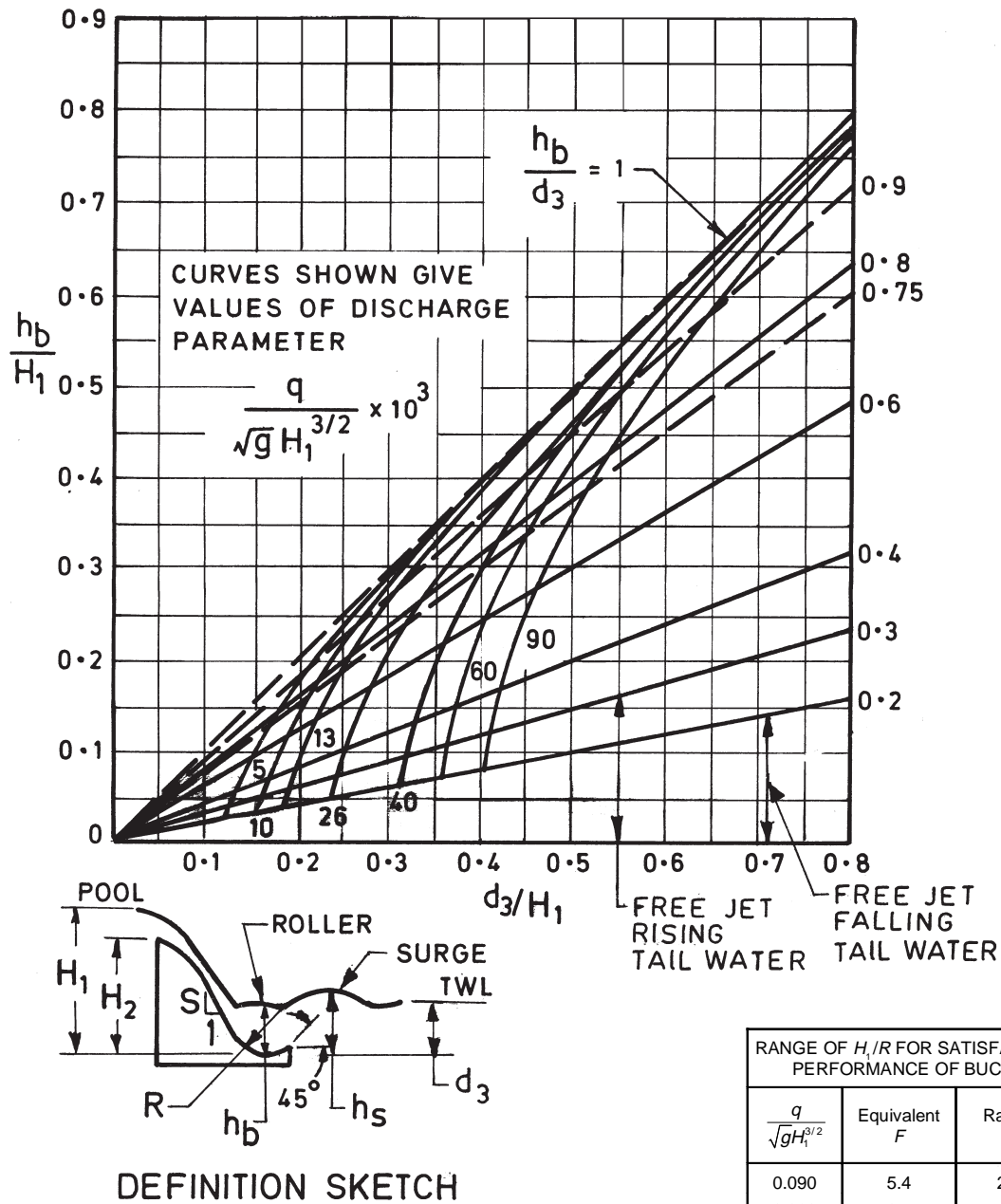


FIG. 3 CONCRETE APRON LAID ON FRESH ROCK



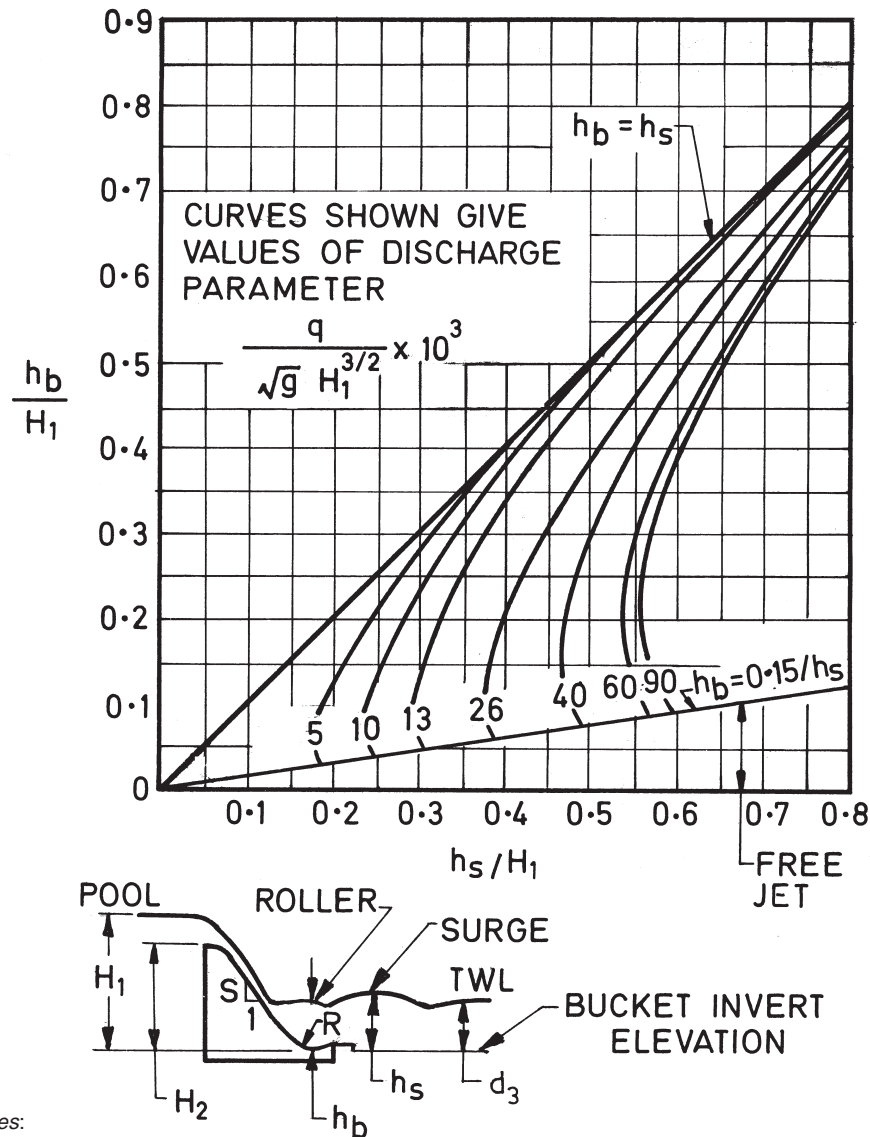
Range of variables:

Spillway slopes ($S:1$) 1:1 to 1.67:1

Lip angle (ϕ) = 45° [the curves may also be used for other lip angles (see 4.2.2.3)]

$H_2/H_1 = 0.68$ to 0.93

FIG. 4 DESIGN OF SOLID ROLLER BUCKET — ROLLER DEPTH



Range of variables:

Spillway slopes ($S : 1$) 1 : 1 to 1.67 : 1

Lip angle (ϕ) = 45° [the chart may also be used for other lip angles (see 4.2.2.3)]

$H_2/H_1 = 0.68$ to 0.93

FIG. 5 DESIGN OF SOLID ROLLER BUCKET — SURGE HEIGHT

NOTE — The design charts given in Fig. 4 and Fig. 5 are not applicable if the spillway crest is submerged by the tail water level in such cases specific model studies shall be conducted to finalize the design.

The discharge parameter (F_D) of the design curves in Fig. 4 and Fig. 5 is given by:

$$F_D = \frac{q}{\sqrt{g} H_1^{3/2}} \times 10^3$$

and has been related to Froude number of the incoming jet as follows:

$$\frac{F_1}{(H_1/d_1)^{3/2}} = \frac{q}{\sqrt{g} H_1^{3/2}}$$

The full range of a spillway discharge should be investigated. When h_b is less than $0.2 d_3$ in the case of falling tailwater and $0.3 d_3$ in the case of rising tailwater, free jet condition may be expected (see Fig. 4).

4.2.2.2 Radius of bucket

The values given in Fig. 4 show the ranges of H_1/R for which good roller action can be expected. The maximum values of H_1/R recommended in the table with Fig. 4 indicate commencement of a pulsating surge downstream of the bucket or commencement of a sloping channel type jump apparently uninfluenced by the presence of the bucket. The minimum values of H_1/R may indicate commencement of eddies in the bucket region and also results in increase of bucket

cost. The bucket, therefore, should not be too deep to set up vortices within the bucket nor too shallow to allow eddies being formed at the junction of the overflow with the upstream end of the bucket circle. The decrease in radius within the range of good roller action increases scour; the rate of increase, however, diminishes with higher value of Froude number. The bucket radius should be chosen to fall within the recommended ranges consistent with economical and structural considerations. There are different formulae for calculating the radius of the bucket. One such formula which has been found to be widely applicable is given below. When the bucket lip angle is 45° , this formula may be used for calculating the bucket radius:

$$\frac{R}{H_1} = 8.26 \times 10^{-2} + 2.07 \times 10^{-3} F_D + 1.4 \times 10^{-5} F_D^2$$

where

F_D = discharge parameter.

$$= \frac{q}{\sqrt{g} H_1^{3/2}} \times 10^3$$

Annex B shows the radius of the bucket as actually provided and as calculated by the formula given above for various existing spillways. Following other formulae are also often used:

$$1) \quad R = \text{bucket radius, in m} \\ = 0.305 \times 10^p$$

$$\text{where } p = \frac{v_i + 6.4H + 4.88}{3.6H + 19.5}$$

$$2) \quad \sqrt{F_1} = 0.09 \frac{R}{d_1} + 1.96$$

where

F_1 = Froude number of jet entering bucket; and

d_1 = depth of flow entering bucket, in m.

$$3) \quad F_1 = 13.0 R^{1/4} - 19.50$$

where

F_1 = Froude number of jet entering bucket.

It should, however, be seen that the value of radius worked out should satisfy the specified range of H_1/R in Fig. 4. Also it should not be less than the minimum allowable radius worked out as in 4.3.2.1. A sample calculation for design of solid roller bucket is given in Annex A.

4.2.2.3 Bucket lip

- a) *Shape and width* — A flat topped lip tends to lower the jet after it leaves the lip and may

reduce the size and strength of the ground roller. This is not desirable from the point of view of prevention of erosion near the lip. Therefore, a downstream slope of 1 in 10 or slightly steeper than that may be given to the top of lip. The width of the lip should not be more than one-tenth of the radius of the bucket. However, the minimum width may be kept as one metre (*see* Fig. 6A). In order to avoid the tendency of the downstream debris riding over the downstream face of the lip, the downstream face may be kept vertical in about 1.0 m depth from top of the lip. A key may be provided below the bucket end sill to protect the bucket against the scour. The depth of scour as given in 6.1.1.3 may be adopted in absence of model studies. In order to protect the edges of the lip, steel plates and angles may be fixed at the edges of the lip (*see* Fig. 6B).

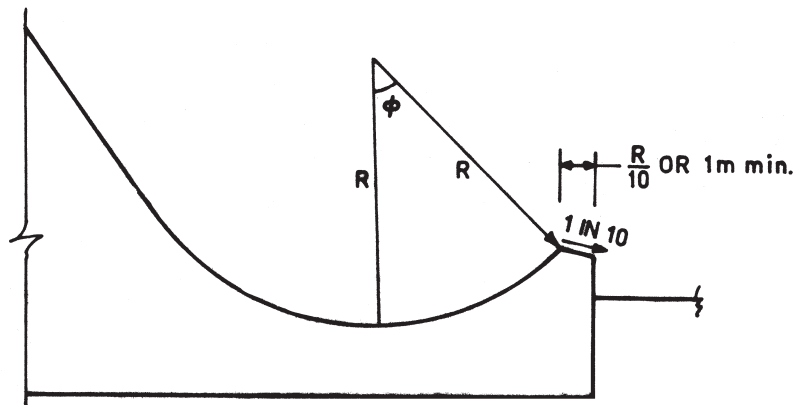
- b) *Lip angle* — A 45° bucket lip angle with the horizontal will be generally satisfactory for most cases where the discharge parameter lies between 30 and 80. But in other cases a smaller lip angle up to 35° would be economical, as it needs lesser depth of tailwater for roller action to begin and may be adopted if found satisfactory as a result of model studies.
- c) *Lip height* — The height of the lip from the invert level depends on the radius of the bucket and the lip angle. The lip level should be kept slightly higher than the bed level downstream so as to avoid entry of bed material in the bucket. If possible, the height of the bucket lip above the invert level may be kept approximately equal to one-sixth of the maximum tailwater depth. Reference to 4.1.2 should be made in this connection.

4.2.2.4 The pressures on the solid roller bucket would be nearly equal to the hydrostatic head measured as the difference in tailwater elevation and the elevation of the point, in the bucket.

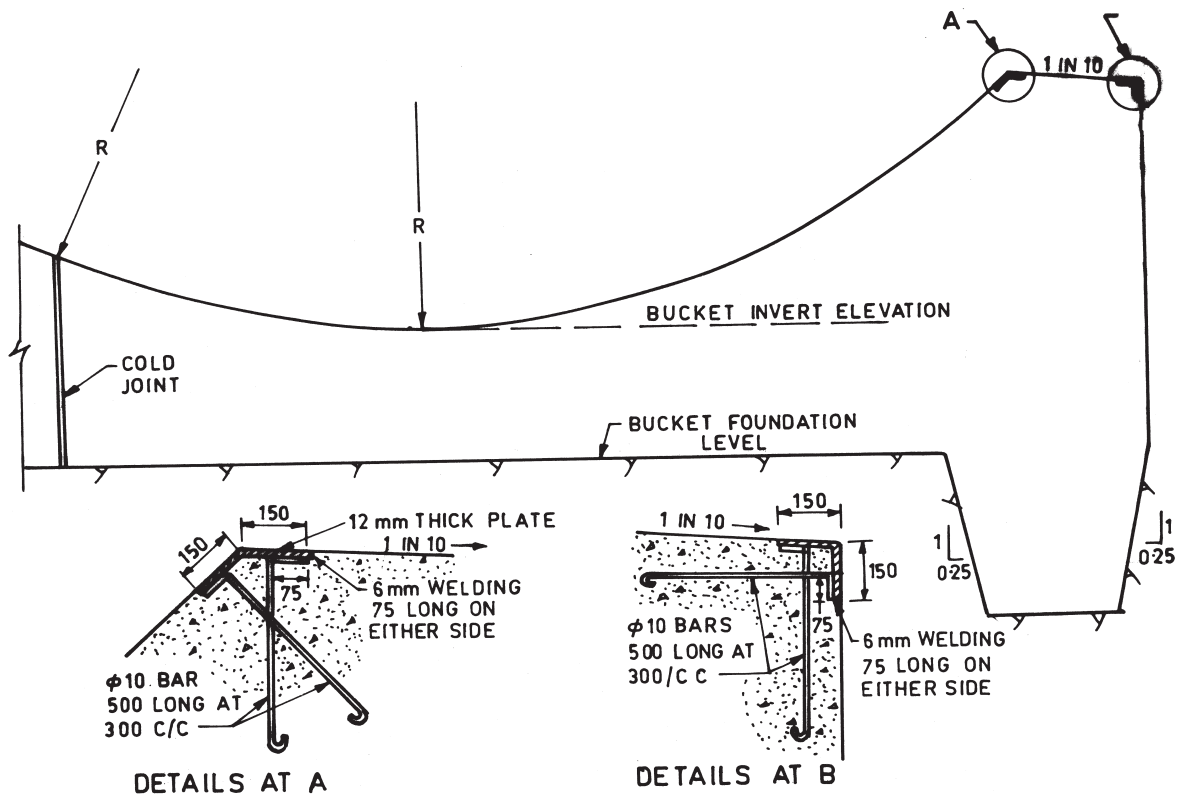
4.2.3 Model Studies

The design criteria given in 4.2.2.1 to 4.2.2.3 will evolve a more or less satisfactory design of solid roller bucket. However, confirmatory model tests are desirable when any one of the following conditions exists:

- a) Sustained operation near limiting conditions is expected,
- b) Discharge per metre width of bucket exceeds $45 \text{ m}^3/\text{s}$,



6A Bucket Lip Shape and Width



6B Lip Elevation

FIG. 6 BUCKET LIP

- c) Velocities entering the bucket exceed 20 m/s,
- d) Eddies appear to be possible downstream of spillway, and
- e) Waves in the downstream channel would cause problems like unstable flow and flow disturbances.

4.2.4 Prototype Examples

A few typical examples of solid roller bucket prototype dimensions for some installations are given in Annex C. These may be used for guidance in the design.

4.3 Hydraulic Design of Slotted Roller Bucket

4.3.1 General

In the slotted roller bucket, a part of the flow passes through the slots, spreads laterally and is lifted away from the channel bottom by a short apron at the downstream end of the bucket. Thus the flow is dispersed and distributed over a greater area providing less violent flow concentrations compared to those in a solid roller bucket. The velocity distribution just downstream of the bucket is more akin to that in a

natural stream, that is, higher velocities at the surface and lower velocities at the bottom. While designing a slotted roller bucket, for high head spillway exceeding the total head (H_1) of 50 m or so, specific care should be taken especially for design of the teeth, to ensure that the performance of teeth will be cavitation free. Specific model tests are therefore desirable to verify pressures on the teeth and the bucket invert should accordingly be fixed at such an elevation as to restrict the sub-atmospheric pressures to the permissible magnitude. The provisions of 4.1.2 and 4.1.4 would also apply in case of the slotted roller bucket.

4.3.2 Design Criteria

The principal features of hydraulic design of the slotted roller bucket consists of determining in following sequence:

- Bucket radius;
- Bucket invert elevation;
- Bucket lip angle; and
- Bucket and tooth dimensions, teeth spacing and dimensions and profile of short apron.

The procedures given in 4.3.2.1 to 4.3.2.4 shall be followed in designing the slotted roller bucket.

4.3.2.1 Bucket radius

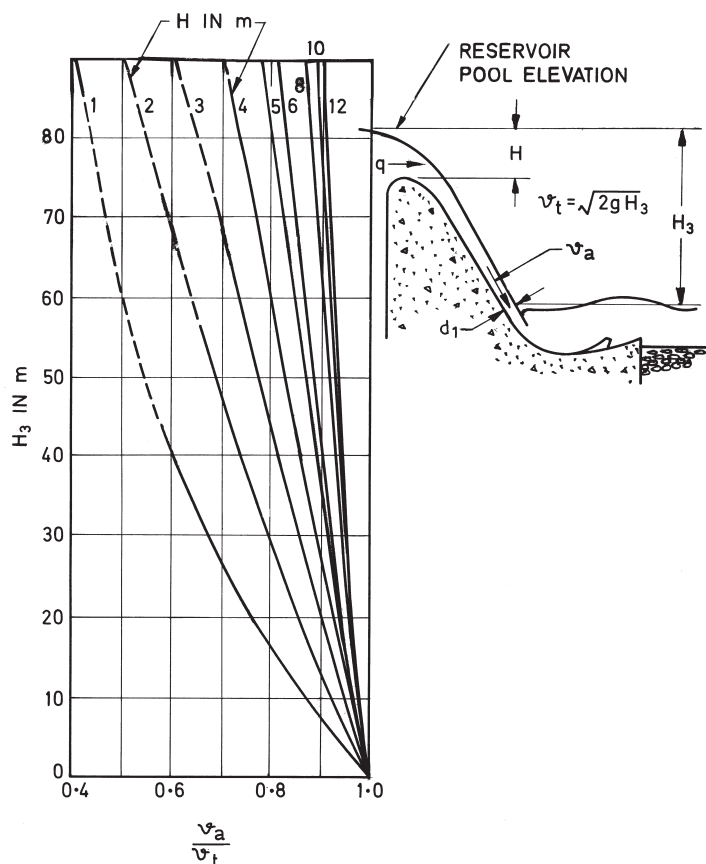
Determine Q (the spillway routed discharge obtained by flood routing calculations) and calculate q the routed discharge per metre of bucket width. Calculate v_t , the theoretical velocity of flow entering bucket, using the formula $v_t = \sqrt{2gH_3}$. Using Fig. 7 find v_a , the actual velocity of flow entering the bucket.

Find $d_1 = \frac{q}{v_a}$. Compute Froude number from

$$F_1 = \frac{v_a}{\sqrt{gd_1}} \text{ for maximum flow and intermediate flows.}$$

Use Fig. 8 with minimum F_1 to find bucket radius

parameter $\frac{R}{d_1 + v_a^2 / 2g}$ from which minimum allowable bucket radius may be computed.



Curves for determination of velocity entering bucket for steep slopes 0.8 : 1 to 0.6 : 1

FIG. 7 DESIGN OF SLOTTED ROLLER BUCKET — VELOCITY OF JET ENTERING BUCKET

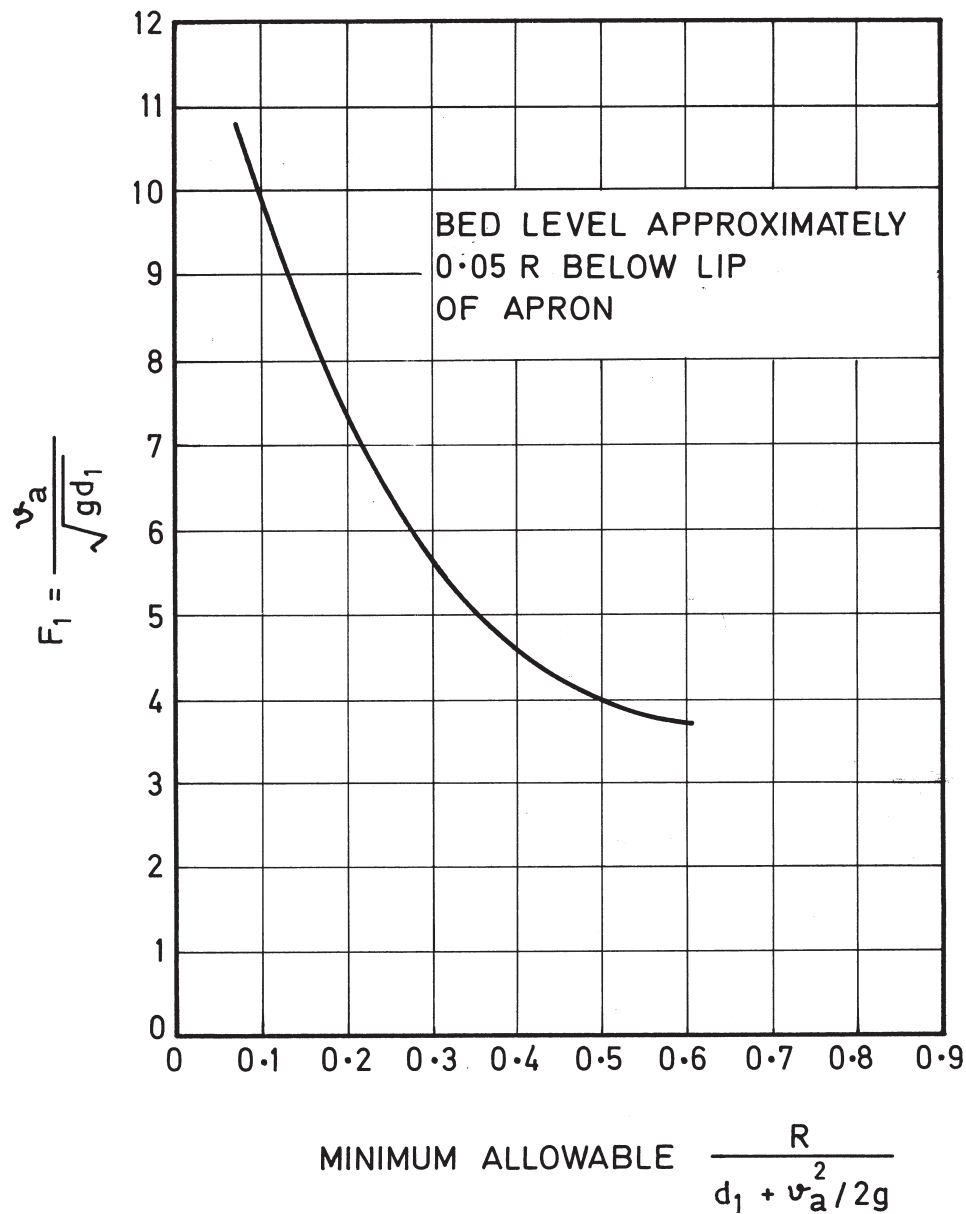


FIG. 8 DESIGN OF SLOTTED ROLLER BUCKET — MINIMUM ALLOWABLE BUCKET RADIUS

4.3.2.2 Bucket invert elevation

From Fig. 9, using values of $\frac{R(\text{used})}{d_1 + v_a^2 / 2g}$ and F_1 , find

$\frac{T_{\text{Min}}}{d_1}$ from which minimum tailwater depth, T_{Min} may

be computed. Repeat the step in Fig. 10 to compute maximum tailwater depth T_{Max} . Set such bucket invert elevation for which the tailwater elevations are between tailwater depth limits determined by T_{Min} and T_{Max} allowing possible retrogression in the bed of the downstream channel. For best performance set such

bucket invert elevation for which tailwater is nearer T_{Min} . Check setting and determine factor of safety against sweep out by computing tailwater sweep out depth, T_s , from Fig. 11. Check the setting for the entire range of discharges.

4.3.2.3 Bucket lip angle

Fix the bucket lip angle in accordance with 4.2.2.3 which is also applicable in the case of slotted roller bucket.

4.3.2.4 Bucket and tooth dimensions, teeth spacing and dimensions and profile of short apron

Use Fig. 12A and Fig.12B to obtain tooth size,

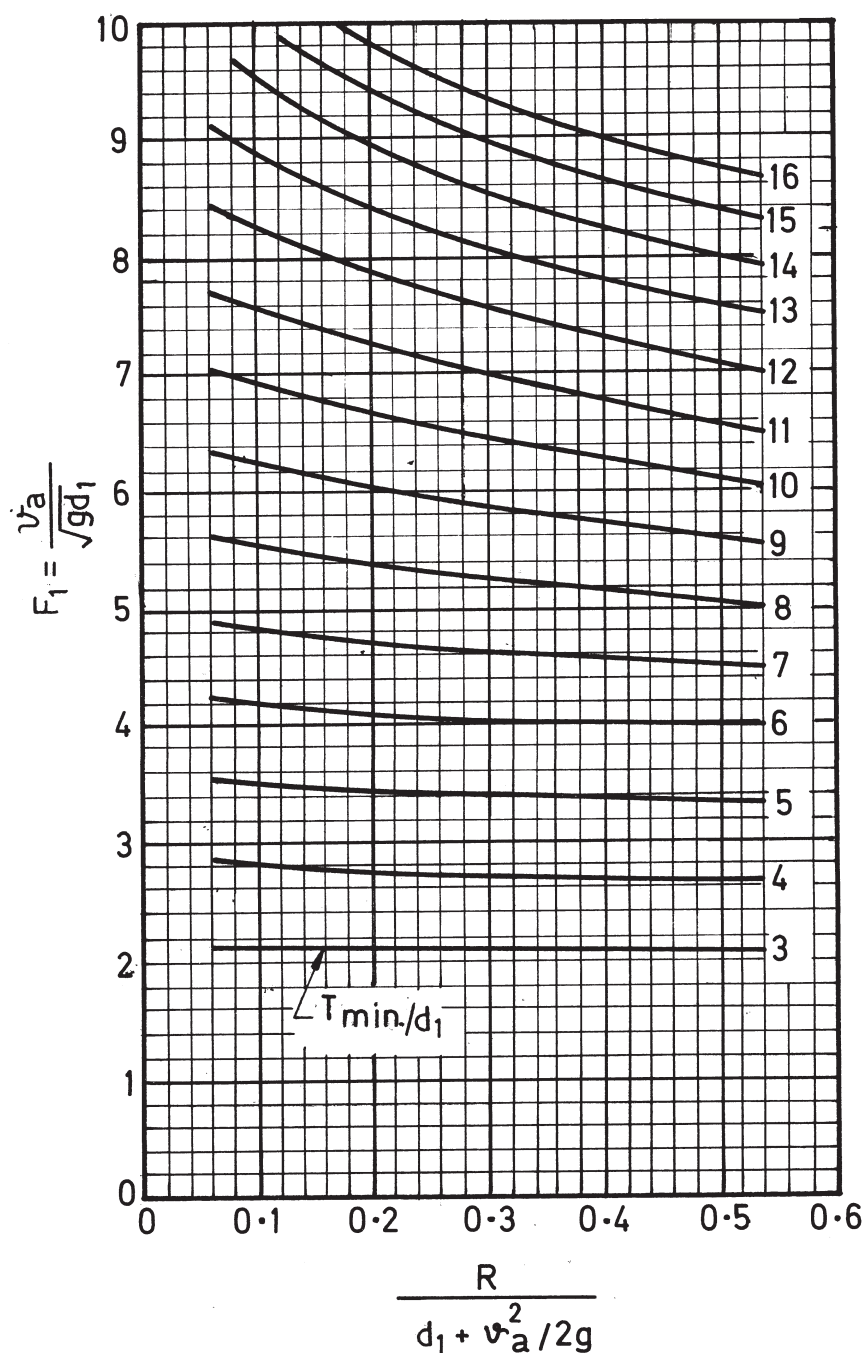


FIG. 9 DESIGN OF SLOTTED ROLLER BUCKET — MINIMUM TAIL WATER LIMIT

spacing, bucket dimensions and profile of short apron. It is desirable that occurrence of negative pressures on bucket teeth be checked on model and possible cavitation damage assessed. If necessary the clear spacing between the teeth can be reduced consistent with minimum working space considerations to reduce sub-atmospheric pressures on the teeth.

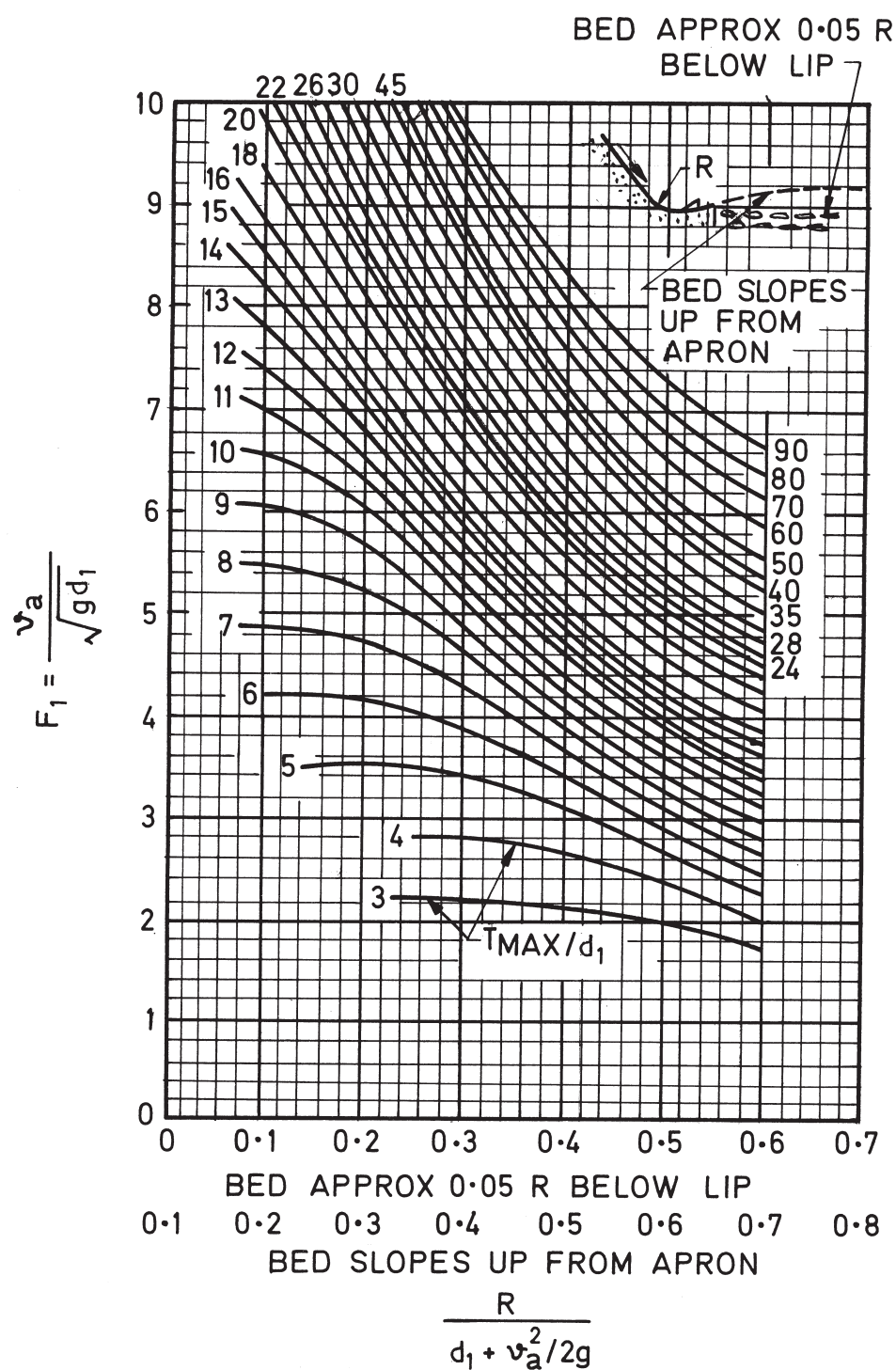
4.3.2.5 A sample calculation given in Annex D may prove helpful in designing a slotted roller bucket.

4.3.3 Model Studies

In the case of slotted roller bucket also, hydraulic model studies shall be done to confirm the design conditions given in 4.2.3 and 4.3.1. It shall be ensured that the teeth perform cavitation free.

4.3.4 Prototype Examples

A few typical examples of slotted roller bucket prototype dimensions for some installations are given in Annex E. These may be used as a guide in the design.



NOTES

- 1 For channel bed elevation 0.05 R below apron lip or lower, use coordinates for bed approx 0.05 R below lip.
- 2 For channel bed elevation higher than 0.05 R below apron lip, use coordinates for bed sloping up from apron.

FIG. 10 DESIGN OF SLOTTED ROLLER BUCKET — MAXIMUM TAIL WATER LIMIT

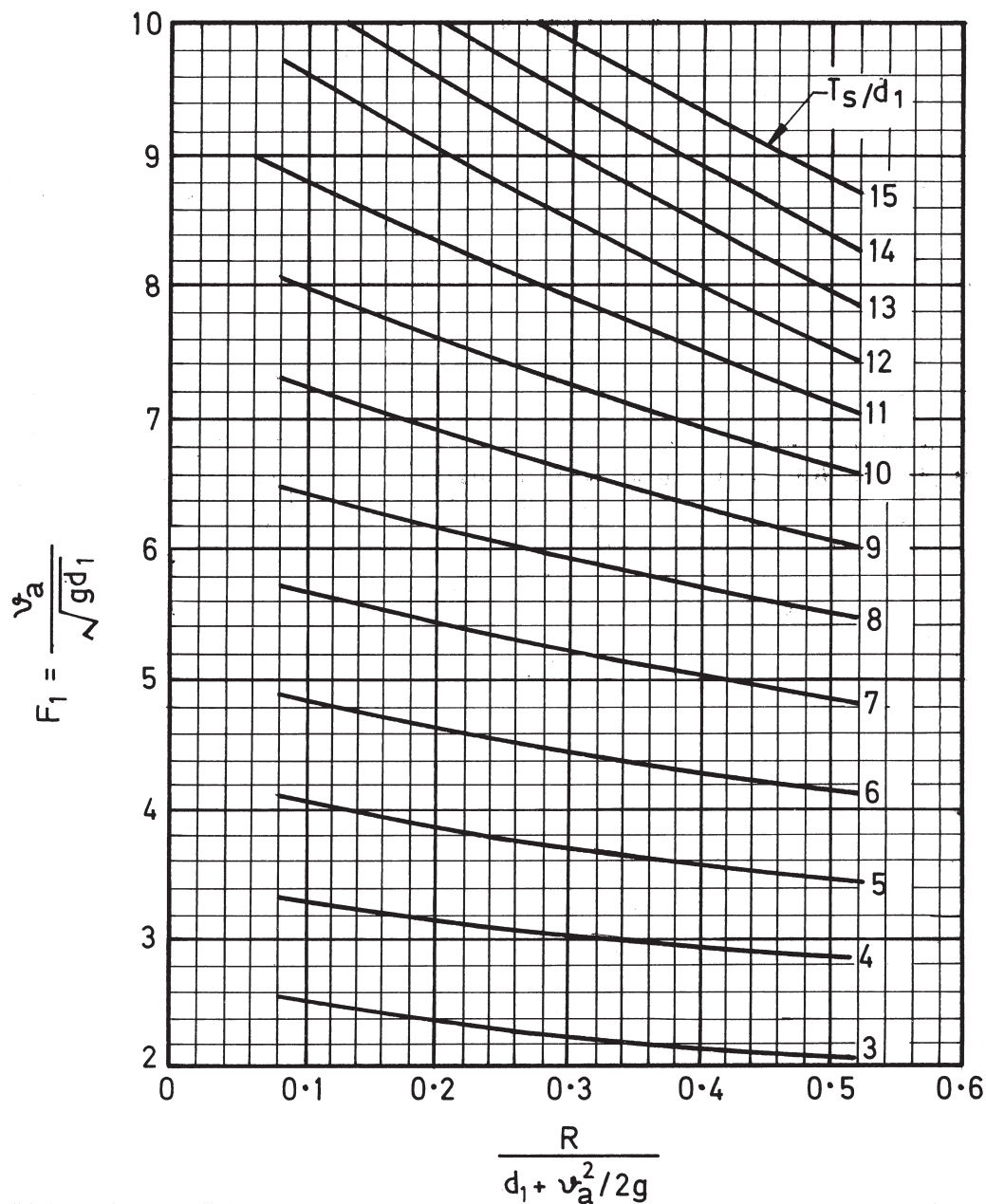


FIG. 11 DESIGN OF SLOTTED ROLLER BUCKET — TAIL WATER SWEEPOUT DEPTH

5 HYDRAULIC DESIGN OF TRAJECTORY/FLIP BUCKET TYPE ENERGY DISSIPATOR

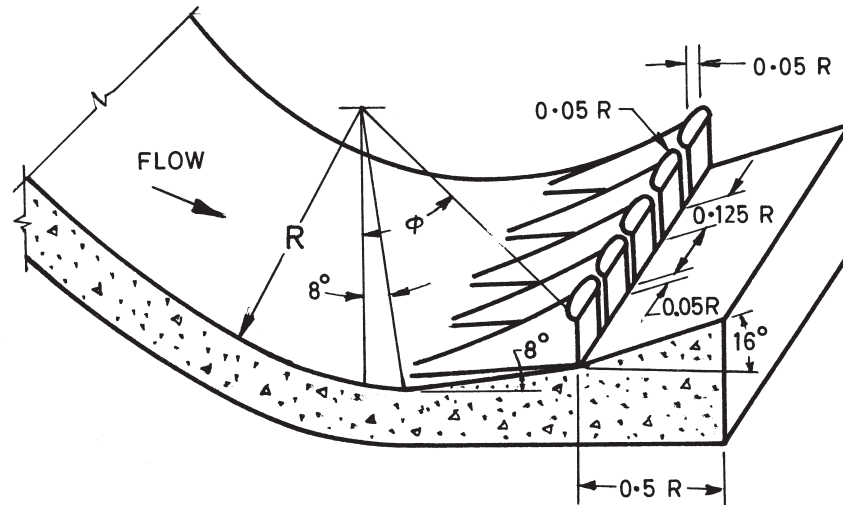
5.1 General

Trajectory bucket type energy dissipator is considered more suitable when,

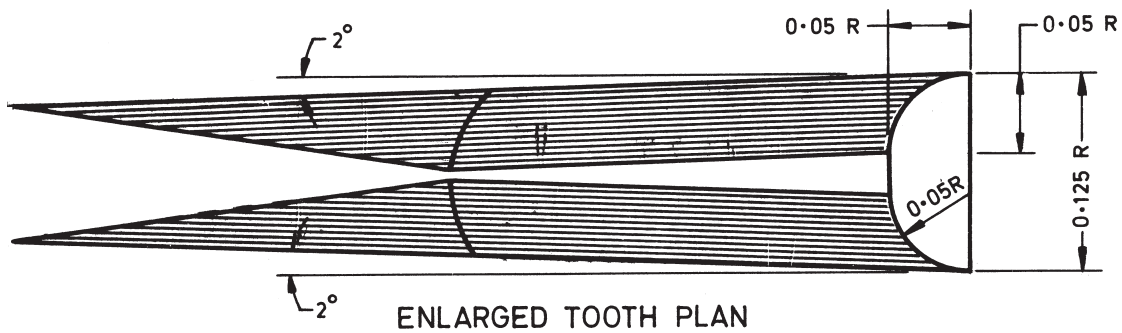
- tailwater depth is much lower than the sequent depth of hydraulic jump, thus preventing formation of the jump;
- by locating at higher level it may be used in case of higher tailwater depths also, if economy permits; and

- bed of the river channel downstream is composed of sound rock.

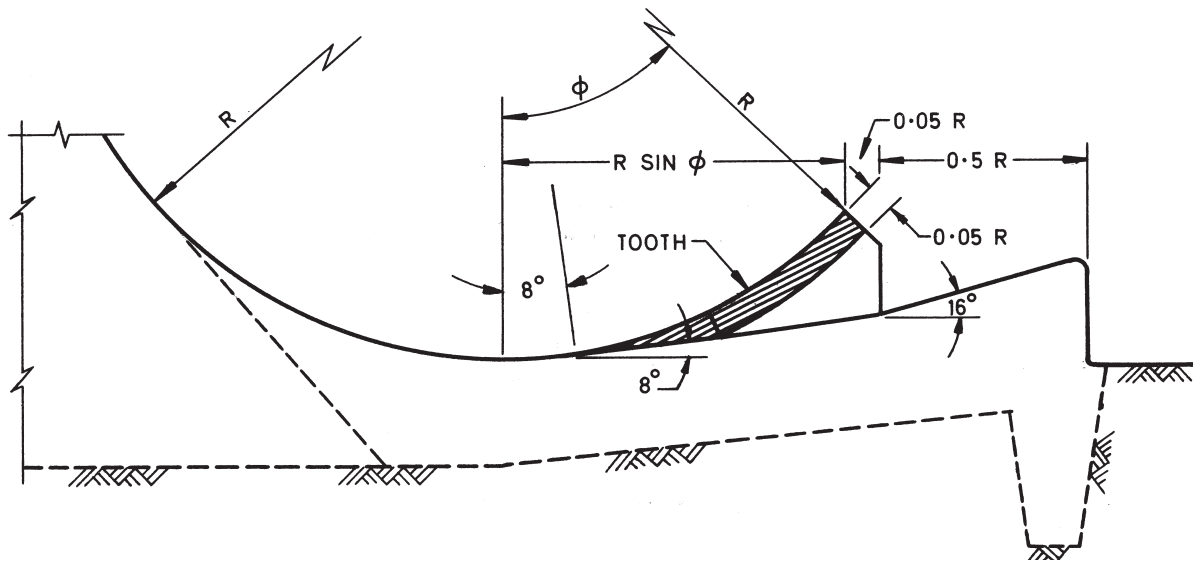
Provision of conventional hydraulic jump type apron or a roller bucket involves considerable excavation in hard strata which can be reduced appreciably. It is also necessary to have sufficient straight reach in the downstream of a ski-jump bucket. The flow coming down the spillway is thrown away in air from the toe of the structure to a considerable distance as a free discharging upturned jet which falls on the channel bed downstream. The hard bed can tolerate the spray from the jet and erosion by the plunging jet would not



12A Dimensions of Slotted Roller Bucket



ENLARGED TOOTH PLAN



12B Tooth Details

FIG. 12 SLOTTED ROLLER BUCKET

pose any significant problem for the safety of the structure. Thus, although there is very little energy dissipation within the bucket itself, possible channel bed erosion close to the downstream toe of the dam is minimized. In the trajectory bucket, only part of the energy is dissipated through interaction of the jet with the surrounding air. The remaining energy is imparted to the channel bed below. The channel bed should consist of sound, hard strata and should be free from laminations, joints and weak pockets to withstand the impact of jet. The design of the trajectory bucket presupposes the formation of large craters or scour holes at the zone of impact of the jet during the initial years of operation and, therefore, the design shall be restricted to sites where generally sound rock is available in the river bed. Special care shall be taken to strengthen weak pockets in the bed located in a length of about 15 m downstream of the bucket.

NOTES

- 1 Slotted trajectory buckets have also been tried in some cases with success.
- 2 Sometimes, pair of trajectory type energy dissipators are so oriented that their jets impinge against each other before they fall into downstream pool below.

5.2 Design Criteria

The principal features of hydraulic design of trajectory bucket consist of determining;

- a) Bucket shape,
- b) Bucket invert elevation,
- c) Radius or principal geometrical parameters of the bucket,
- d) Lip elevation and lip angle,
- e) Trajectory length, and
- f) Estimation of scour downstream of the spillway.

The procedure given in 5.2.1 to 5.2.5 shall be followed in designing trajectory bucket.

5.2.1 Bucket Shape

The performance of the trajectory bucket is judged by the trajectory height and the length of throw in the flip action. Generally a circular shape is preferred from practical consideration. Hence, the design criteria for a circular trajectory bucket has been discussed in this standard.

5.2.2 Bucket Invert Elevation

The fixation of bucket invert elevation depends on the site and tailwater conditions. For a clear flip action, the lip shall have to be kept above the maximum tailwater level. When the bucket is placed near the natural bed level it will not only be economical but also there will be a beneficial ground roller just below the endsill which would help in piling up material against the endsill. Under these conditions there is less possibility of erosion immediately downstream of the bucket. Therefore, with the considerations of economy and beneficial ground roller action, an attempt should be made to fix the bucket invert as close to the ground level as possible. In such cases the bucket invert is decided so as to provide a minimum concrete cover of 1.5 m over the bed rock. Also beyond certain submergence, the lip may turn the ski action into roller action. Fig. 13 gives the submergence (d_4) at which ski action would turn into roller action. The tailwater interference in the performance of the trajectory bucket will change the flow conditions and may result in heavy sub-atmospheric pressures at the lip. A submergence of more than 70 percent of the depth required for formation of hydraulic jump may adversely affect proper performance of the trajectory bucket. The safe maximum submergence may be assumed to be equal

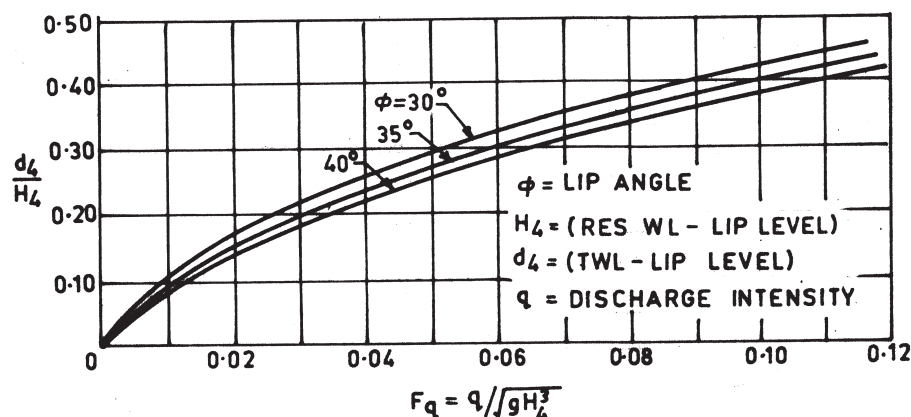


FIG. 13 SUBMERGENCE d_4 AT WHICH SKI ACTION WOULD TURN INTO ROLLER

to the critical depth (d_c) over the lip elevation. Sometimes the trajectory buckets are located at higher level on the spillway glacis to facilitate the construction of power house at the toe of spillway. In case of such high level trajectory buckets it is necessary to consider the effect of scour downstream which may cause the sliding of abutment slopes if the geological conditions are not favourable. Also the sprays from the water jet may spoil the nearby electrical installations, which need to be protected.

5.2.2.1 Hydraulic forces acting on a trajectory bucket are of interest in the structural design of the bucket. Theoretical studies, model studies and prototype data indicate that bottom pressures change continuously throughout the bucket and a function of the entering velocity and depth of flow, radius of curvature of the bucket and angle of deflection of the flow. The concept of centrifugal force gives an indication of the effects of independent variables. The centrifugal force together with the corresponding water depth in the bucket would indicate the pressure on the bucket. The equation involving terms applicable to trajectory bucket pressures can be written as:

$$P = \left(\frac{v_a^2}{gR} + 1 \right) \gamma d_1$$

where

- P = bucket pressure, in t/m^2 ;
- γ = weight of water, in t/m^3 ;
- v_a = actual velocity of flow entering bucket, in m/s ;
- g = acceleration due to gravity, in m/s^2 ;
- R = radius of bucket, in m ; and
- d_1 = depth of flow entering bucket, in m .

5.2.2.2 Figure 14 presents maximum theoretical bucket pressures for velocities varying from 10 to 45 m/s and radius/depth ratios varying from 4 to 10. Actual pressures vary considerably over the bucket. However, the curves shown in Fig. 14 shall be used to estimate the hydraulic load per square metre of the bucket surface. The design of training walls adjacent to the bucket should also allow for these pressures. Actual variation of pressure along bucket profile and along the retaining walls, if required, can be ascertained with the help of model studies.

5.2.3 Radius of Bucket

The pressure distribution on the bucket and the trajectory length are affected by the radius. To maintain the concentric flow and to avoid the tendency of the water to spring away from the bucket, the radius has to be substantially large so that the streamline distribution

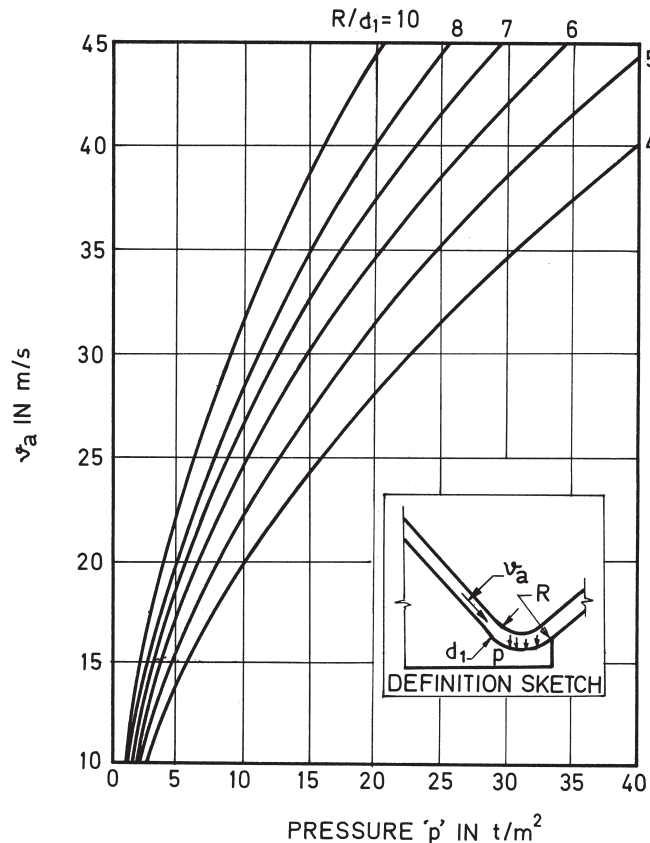


FIG. 14 DESIGN OF TRAJECTORY BUCKET — THEORETICAL BUCKET PRESSURES

of the flow is not altered by the floor pressure. The radius of the bucket (R) should not be less than 3 times the maximum depth of flow (d_1) entering the bucket to avoid separation tendencies in the bucket. Another criterion for the radius of bucket obtained by experience and satisfactorily used for several designs is that the radius can be taken to be equal to 0.6 to 0.8 times the geometric mean of the depth of flow over the spillway and the total fall between upstream reservoir pool elevation and the jet surface on the bucket, that is $R = (0.6 \text{ to } 0.8) \sqrt{H.H_s}$. These guide rules shall be used for preliminary design. The higher value of 0.8 should preferably be used for preliminary design. A closer estimate of the radius to be actually used shall, however, be made by model tests by finding the actual pressure conditions existing and avoiding hurdling conditions on the bucket.

5.2.4 Lip Elevation and Lip Angle

The lip angle affects the horizontal throw distance. The factors affecting the horizontal throw distance also include the initial velocity of the jet and the difference in elevation between the lip and the tailwater. Normally adopted lip angle is between 30° and 40° . Greater the exit angle within this range greater will be the distance of throw. But as the jet impinges on the tailwater at a steeper angle which results in deeper scour, the final choice depends upon the minimum throw permissible under the local rock conditions. For submerged lips the lower lip angle of 30° may be adopted to minimize sub-atmospheric pressures on the lip.

5.2.4.1 The lip shall be made flat in case tailwater level is lower than the lip level. However, if the tailwater level is higher than the bucket lip level, the lip shall slope downstream about 1 in 10. In some cases necessity of aeration may arise which may be finalized after model studies.

5.2.5 Trajectory Length

5.2.5.1 The following expression may be used for calculating the horizontal throw distance:

$$\frac{X}{H_v} = \sin 2\phi + 2 \cos \phi \sqrt{\sin^2 \phi + Y/H_v}$$

where

- X = horizontal throw distance from bucket lip to the centre point of impact with tailwater, in m;
- Y = difference between the lip level and tailwater level, sign taken as positive for tailwater below the lip level and negative for tailwater level above the lip level, in m;
- H_v = velocity head of jet at the bucket lip, in m; and
- ϕ = bucket lip angle with the horizontal in degrees. For the conditions when Y is

negative, model studies may be carried out to confirm the values of horizontal throw distance (X) and vertical distance (a).

5.2.5.2 Vertical distance of throw above the lip level may be calculated from the following formula:

$$a = \frac{v_a^2 \sin^2 \phi}{2g}$$

where

- a = vertical distance from the lip level to the highest point of the centre of jet, in m;
- v_a = actual velocity of flow entering the bucket, in m/s;
- ϕ = bucket lip angle with the horizontal, in degrees; and
- g = acceleration due to gravity, in m/s^2 .

5.2.5.3 Figure 15 presents throw distance curves for lip angles of 0 to 45° based on the expression given in 5.2.5.1. This shall be used for judging the point of impact of the jet. The actual throw distance may be less than indicated depending upon spillway energy loss, air entrainment in the jet, etc.

5.2.6 Estimation of Erosion at the Point of Impact

5.2.6.1 The factors governing scour below trajectory buckets are the discharge intensity, height of fall, water level, lip angle, mode of operation of spillway, degree of homogeneity of rock, type of rock, time factor involved in the process of scour, etc. An evaluation of the extent of scour has to consider the combined effect of all these factors which is very difficult in practice. However, restricting the analysis to the correlation of the scour depth with the two dominant factors, namely, discharge intensity (q) and the total head (H_4), the depth of scour (d_s) can be worked out by the following equation:

$$d_s = m (q H_4)^{0.5}$$

where

- d_s = depth of scour in m below tailwater level;
- m = constant (0.36 for minimum expected scour) (0.54 for probable scour under sustained spillway operation) (0.65 for ultimate scour);
- q = discharge intensity (m^3/s)/m; and
- H_4 = reservoir pool elevation — bucket lip elevation, in m.

NOTES

- 1 Ultimate scour means the final stabilised scour.
- 2 Probable scour means the scour which may reasonably be expected in any individual case of sustained spillway operation.
- 3 Minimum scour means the minimum scour in any case.

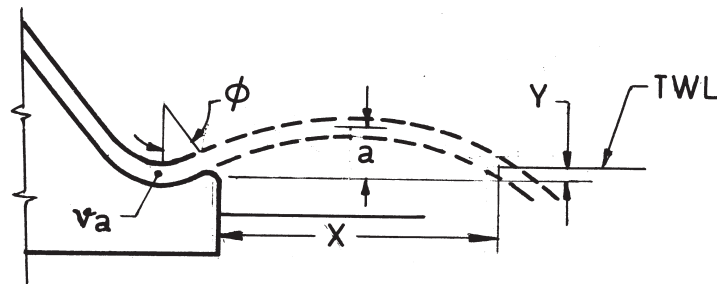
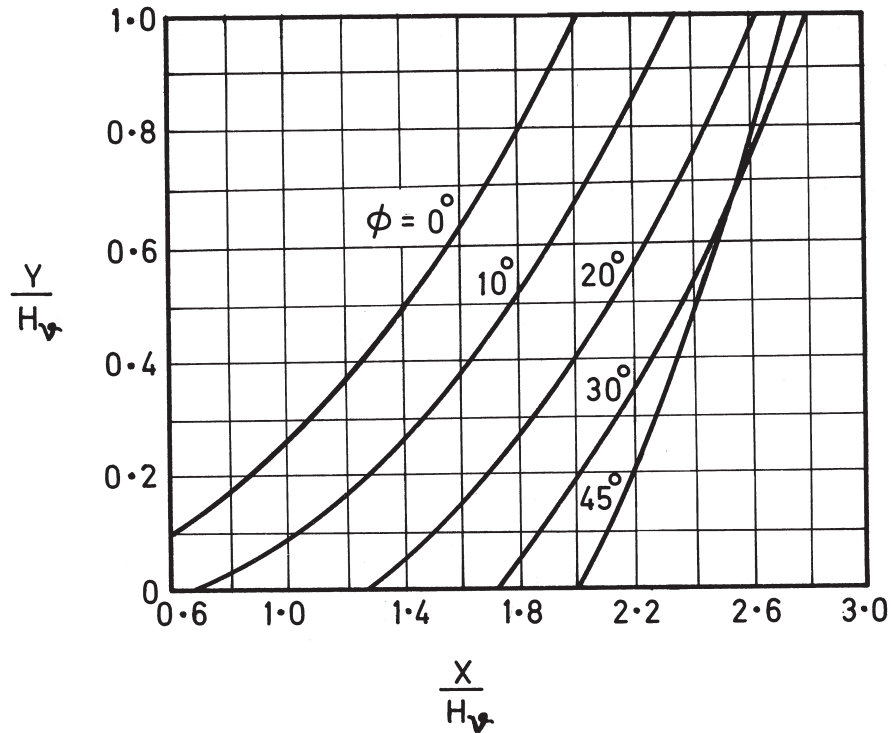


FIG. 15 DESIGN OF TRAJECTORY BUCKET — THROW DISTANCE

5.2.6.2 Figure 16 presents scour depth curve for minimum expected scour, probable scour under sustained spillway operation and ultimate scour based on the expression given in 5.2.6.1. This shall be used for estimating the scour depth (d_s).

5.2.6.3 Another formulae to work out the probable scour is also given below for guidance:

$$d_s = 1.9 H_3^{0.225} q^{0.54}$$

when

d_s = depth of scour, in m; and

H_3 = reservoir pool elevation minus tailwater elevation, in m.

5.2.6.4 During construction stages, the temporary spill levels are at much lower elevation than the final crest level thus reducing the height of fall. Therefore, the trajectory will have a shorter range and may, in certain circumstances lead to overall conditions causing scour closer to the bucket. In order to protect the endsills from undermining a cut-off may be provided and the excavated trench should immediately be backfilled with concrete, flush with the original ground level. The provision of a concrete apron of about 10 to 15 m length downstream may also be considered to prevent the scour near the bucket lip where the condition of rock is such that it is likely to be eroded. Provide minimum thickness of apron of 1 m and it should be properly anchored over fresh rock.

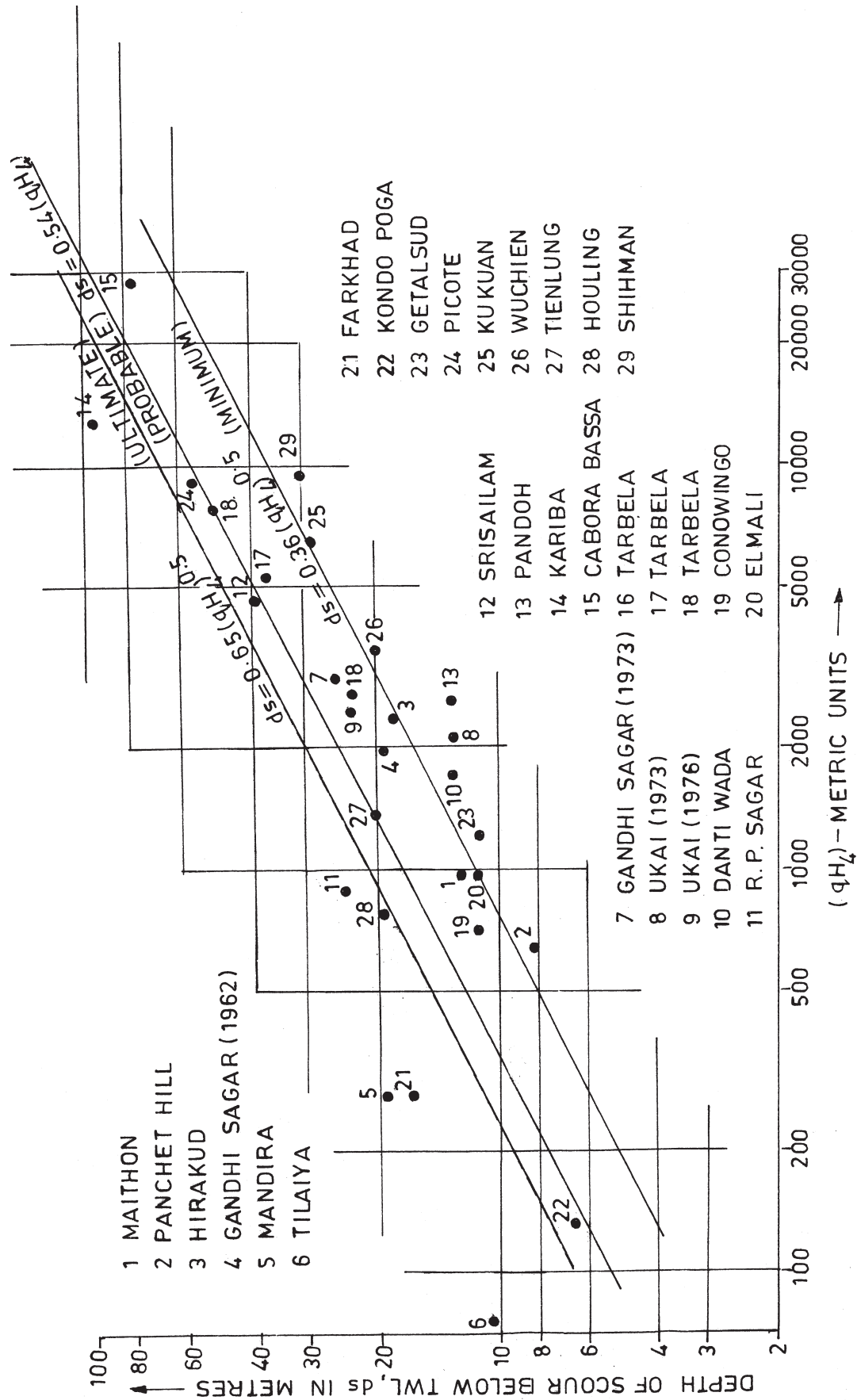


FIG. 16 DESIGN OF TRAJECTORY BUCKET — ESTIMATION OF SCOUR DOWNSTREAM OF BUCKET

5.2.6.5 Plunge pool design

Pre-excavated plunge pools are provided downstream of ski-jump bucket to create a water cushion whose geometric characteristics must be such that it will reduce the energy of the flow and consequently dampen the uncontrolled erosion, which will otherwise endanger the stability of the structure. In order to design plunge pool, hydraulic parameters such as ski-jump throw distances for the entire range of discharges and the location and magnitude of deepest scour are considered. These can be obtained from the hydraulic model studies. Besides hydraulic parameters, some other factors such as the geologic and morphologic characteristics of the jet impact area are also taken into account.

5.2.7 Model Studies

The trajectory bucket shall be model tested to ensure satisfactory hydraulic performance of the bucket which is judged by the trajectory height, the throw distance and also the depth and extent of scour. It shall be also ensured that sub-atmospheric pressures do not exist on the bucket profile and on the bucket lip.

5.3 Prototype Examples

Annex F gives a few typical examples of trajectory bucket prototype dimensions for some installations. These may be used as a guide in the design.

6 TRAINING AND DIVIDE WALLS

6.1 With the provision of a solid or slotted roller bucket or trajectory bucket at the toe of the spillway, the design of the end training walls and intermediate divide walls on the spillway in respect of their lengths, top levels, foundation levels, etc, assume importance.

6.1.1 Where the model studies are not carried out the height, length and foundation of training wall in the case where a roller bucket has been adopted may be worked out as follows.

6.1.1.1 Height of training wall

In the bucket portion the top of the wall may be kept higher by 1.5 m above the maximum water level in the bucket or as required according to the earth dam profile adjacent to it. The height of the wall in the surge portion should rise at least to an elevation $h_s + 1.5$ m, where h_s is the maximum surge height. The surge height may be worked out as shown in Annex A. The distance of surge (S_d) can be obtained from Fig. 18. The wall can be given a trapezoidal shape for economy as indicated in Fig. 17. The top of the wall beyond the surge portion should be kept at least 1.5 m above the maximum tailwater level or higher, if required, according to the earth dam profile adjoining the wall depending upon the layout of the dam. The following empirical relationship has been found to be generally suitable in working out the free board B and may be adopted for

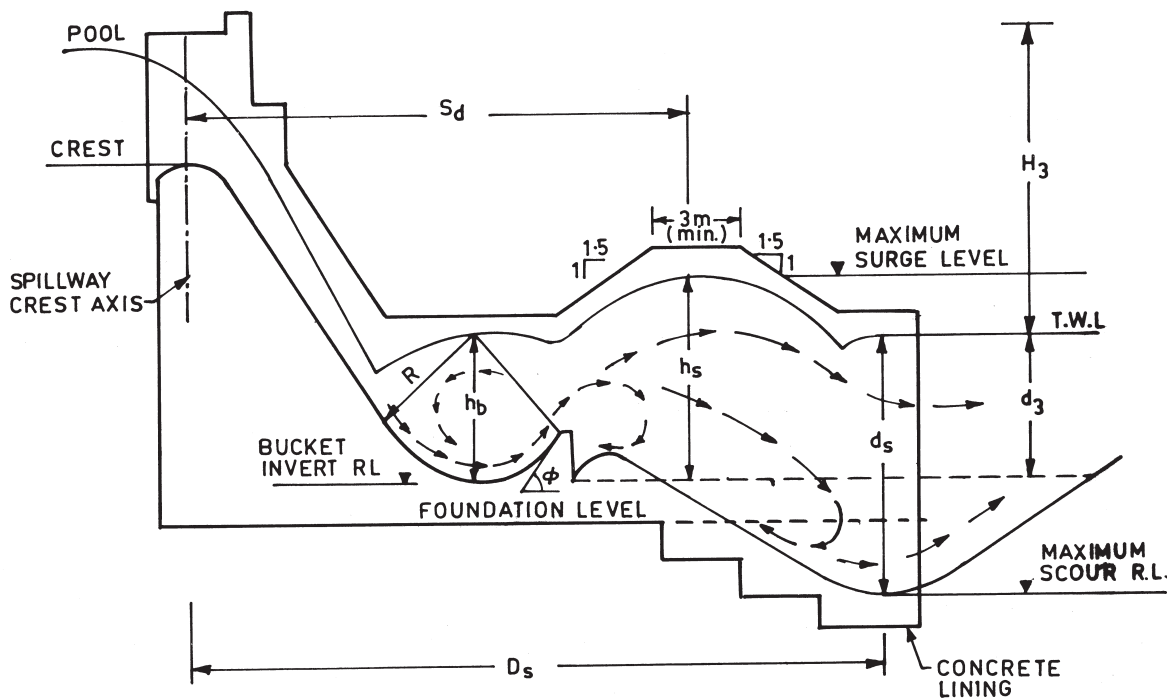


FIG. 17 DEFINITION SKETCH FOR TOP PROFILE OF TRAINING WALL AND SCOUR AND SURGE DISTANCES

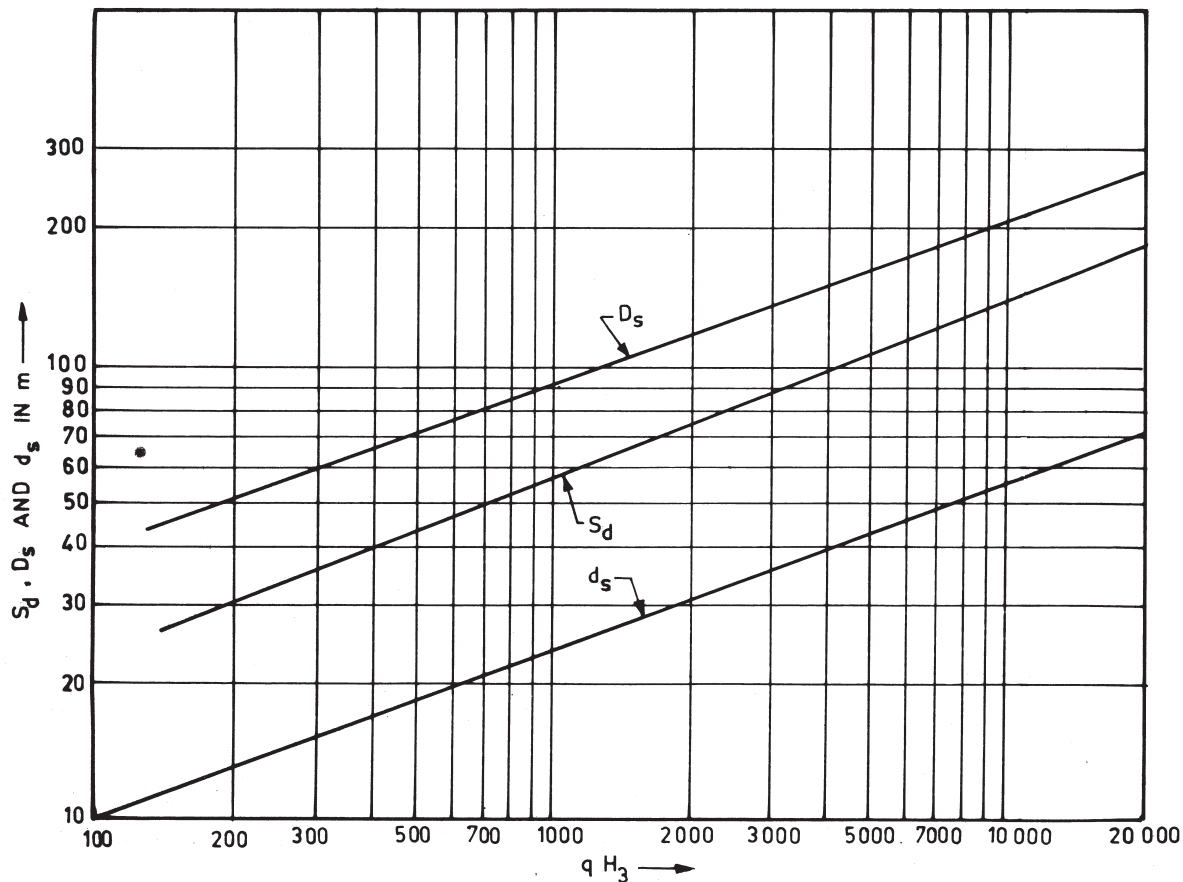


FIG. 18 TRAINING AND DIVIDE WALLS SCOUR DEPTH AND DISTANCE AND SURGE DISTANCE

preliminary designs (later to be confirmed by hydraulic model studies and detailed calculations) $\sqrt{F.B.}$ (in metre) = $0.0305 (V_a + D_2)$ where V_a = actual velocity of flow entering the bucket in m/s, and D_2 = sub-critical depth of flow in bucket including the boil height, etc, in metre.

6.1.1.2 Length of training wall

The length of the training wall may generally be fixed as per the following criteria:

- The wall should be extended downstream beyond the surge portion by about 3 m or as dictated by the downstream toe of the envelope of the earth dam, powerhouse, etc.
- If the toe of the envelope is resting on erodible alluvium bed the training wall should be extended beyond the toe at least by 15.0 m.
- If the bed strata is erodible the wall should be extended beyond the location of the deepest scour by about 5.0 m.

A splay wall connecting the bank may be provided, if required, at the end of the training wall to avoid erosion behind the wall. In some installations the spillway flow is required to be separated from an adjoining structure like an earth dam toe, power house tail channel, canal or any other structure. In such cases the optimum lengths and top levels shall be decided on the basis of the water and scour profiles obtained from the model studies. In some cases intermediate divide walls are also provided to separate the flow from adjoining buckets at different elevations. Their top levels and lengths shall also be decided on the basis of model studies.

6.1.1.3 Foundation of the training wall

The wall should be founded about 2.0 m, lower than the maximum scour level as worked out from Fig. 18 if competent foundation rock is not available above the scour level. In order that foundation rocks may not get exposed and undermined, it is necessary to provide the foundation of the wall either down to the scour levels observed on the model or to a higher level, if

competent foundation rocks are available at that level. In the later case, a concrete lining of about 1.0 to 1.5 m thickness should be provided below the foundation level of the wall down to the anticipated scour level if the wall has been extended beyond the bucket. For the spillways where the model studies are carried out, the scour envelope should be adopted for the purpose of founding the wall or protective lining below it. In cases where model studies are not conducted and where a roller bucket is provided, the maximum probable scour depth (d_s), the distance (D_s) from the spillway crest axis and the maximum probable distance of the surge (S_d) from spillway crest axis (*see* Fig. 17) may be calculated with the use of the curves given in Fig. 18.

The graph shown in Fig. 18 indicates probable parameters and may be adopted for guidance only.

6.1.2 In case of a trajectory bucket, the training wall should normally be extended by about 10 m beyond the endsill as per requirement to overcome the formation of return flow eddies, etc, and thereby avoiding the entry of the downstream bed material into the bucket in the event of one or two of the end crest gates not getting opened. It may be preferable to flare the training walls beyond the lip so as to provide aeration to the ski-jump trajectory. It has also been observed in the case of the prototype trajectory bucket that the normal depth of the air-water mixture would be as high as 2.5 times the normal depth of clear water. As it is not possible to represent the air-entrainment in the hydraulic model test, it is advisable to provide the freeboard of the wall considering the following empirical relation, which is found to be generally suitable for preliminary design (later to be confirmed by hydraulic model studies and detailed calculations).

$$\text{Freeboard} = 0.61 + 0.037 \, 1 \, v_a \, d_1^{1/3} \text{ (in m)}$$

where

v_a = actual velocity of flow entering bucket, in m/s; and

d_1 = depth of flow entering bucket, in m.

The foundation of the training wall and/or lining below it may be taken down to the scour level worked out as indicated in 5.2.6.

7 REGULATION

7.1 All the spans of a spillway having a roller bucket at the toe have to be operated equally and simultaneously. In case of trajectory bucket this condition is not necessary unless objectionable flow conditions and return eddies are formed downstream of the bucket.

8 RETROGRESSION OF DOWNSTREAM CHANNEL

8.1 The design of a roller or trajectory bucket is primarily based on the tailwater rating curve observed or assumed. These tailwater rating curves and their accuracy shall be thoroughly checked before finalizing the designs. Allowance shall also be made for the retrogression of the downstream channel bed and consequent lowering of the tailwater levels. Consequently a 10 percent variation in tailwater depth may be taken into account in design calculations. The actual observations of tailwater levels downstream of the spillway shall be taken every year and shall be compared with the tailwater rating curve adopted for the design to evaluate the percentage retrogression in the tailwater level.

9 MAINTENANCE AND INSPECTION

9.1 It is preferable to make bucket starting from tangential point on spillway face to bucket lip in granite stones or to provide an overlay with special wear-resistant material.

9.2 In order to avoid the danger of loose material downstream of the roller bucket being picked up and carried into the bucket and consequent possible abrasion damage to the bucket, it is desirable to clear an area up to about 50 to 100 m downstream of bucket of all loose material every year before monsoon. It is also desirable to inspect every year the spillway to assess the damage to bucket surface, bucket teeth lip, training walls and erosion downstream. Damage to any surface shall be immediately repaired. Weak pockets of river bed downstream which might have been eroded should be filled with concrete. Damage to the foundations of bucket lip, training walls, etc, shall also be immediately repaired.

ANNEX A
(Clauses 4.2.2.1 and 6.1.1.1)

DESIGN OF SOLID ROLLER BUCKET — SAMPLE CALCULATIONS

Given

Discharge per metre width of spillway (q) = 55.30 m³/s

Reservoir pool elevation = E_L 128.02 m

Tailwater elevation = E_L 99.67 m

Spillway crest elevation = E_L 116.74 m

i) *Bucket Invert Elevation*

Assume

Bucket invert elevation = 79.25 m

Compute,

$$\begin{aligned} H_1 &= \text{Reservoir pool elevation minus bucket invert elevation} \\ &= 128.02 - 79.25 \\ &= 48.77 \text{ m} \end{aligned}$$

$$\begin{aligned} H &= \text{Reservoir pool elevation — Crest elevation} \\ &= 128.02 - 116.74 \\ &= 11.28 \text{ m} \end{aligned}$$

$$\begin{aligned} H_3 &= \text{Reservoir pool elevation — Tailwater elevation} \\ &= 128.02 - 99.67 \\ &= 28.35 \text{ m} \end{aligned}$$

$$\begin{aligned} d_3 &= \text{Tailwater elevation — Bucket invert elevation} \\ &= 99.67 - 79.25 \\ &= 20.42 \text{ m} \end{aligned}$$

$$\therefore \frac{d_3}{H_1} = \frac{20.42}{48.77} = 0.42$$

Discharge parameter,

$$\begin{aligned} F_D &= \frac{q}{\sqrt{g}H_1^{3/2}} \times 10^3 \\ &= \frac{55.30}{\sqrt{9.81} \times (48.77)^{3/2}} \times 10^3 \\ &= 51.84, \text{ say } 52.00 \end{aligned}$$

From Fig. 4 for

$$F_D = \frac{q}{\sqrt{g}H_1^{3/2}} \times 10^3 = 52 \text{ and } \frac{d_3}{H_1} = 0.2$$

$$\text{read } \frac{h_b}{H_1} = 0.315$$

$$h_b = 0.315 \times 48.77 = 15.36 \text{ m}$$

$$\therefore \frac{h_b}{d_3} = \frac{15.36}{20.42}$$

$$= 0.752$$

Good energy dissipation is obtained when $\frac{h_b}{d_3}$

is between 0.75 and 0.90.

$$\begin{aligned} \text{Now, } v_t &= \sqrt{2gH_3} \\ &= \sqrt{2 \times 9.81 \times 28.35} \\ &= 23.58 \text{ m/s} \end{aligned}$$

From Fig. 7 for

$$H = 11.28 \text{ m and } H_3 = 28.35 \text{ m}$$

$$\text{read } \frac{v_a}{v_t} = 0.95$$

$$\begin{aligned} v_a &= 0.95 \times v_t \\ &= 0.95 \times 23.58 \\ &= 22.40 \text{ m/s} \end{aligned}$$

$$\begin{aligned} d_1 &= \frac{q}{v_a} \\ &= \frac{55.30}{22.40} \\ &= 2.47 \text{ m} \end{aligned}$$

$$\begin{aligned} \text{Now } F_1 &= \frac{v_a}{\sqrt{gd_1}} \\ &= \frac{22.40}{\sqrt{9.81 \times 2.47}} \\ &= 4.55 \end{aligned}$$

$$\begin{aligned} d_2 &= \frac{d_1}{2} \left\{ \sqrt{1 + 8 \times F_1^2} - 1 \right\} \\ &= \frac{2.47}{2} \left\{ \sqrt{1 + 8 \times (4.55)^2} - 1 \right\} \\ &= 14.70 \text{ m} \end{aligned}$$

$$\begin{aligned}\therefore \frac{d_3}{d_2} &= \frac{20.42}{14.70} \\ &= 1.39\end{aligned}$$

Good energy dissipation is obtained when $\frac{d_3}{d_2}$ is

between 1.1 and 1.4

Setting of bucket invert elevation is therefore acceptable.

From Fig. 5 for,

$$\frac{q}{\sqrt{g}H_1^{3/2}} \times 10^3 = 52 \text{ and } \frac{h_b}{H_1} = 0.315$$

$$\text{read } \frac{h_s}{H_1} = 0.53$$

$$\begin{aligned}\text{Therefore } h_s &= 0.53 \times 48.77 \\ &= 25.85 \text{ m}\end{aligned}$$

Compute h_b and h_s for the full range of spillway flows.

Determine maximum elevation of bucket roller and surge.

$$\begin{aligned}\text{Compute } H_3 &= \text{Reservoir pool elevation} - \text{tailwater elevation} \\ &= 128.02 - 99.67 = 28.35 \text{ m}\end{aligned}$$

$$\begin{aligned}\text{Therefore } qH_3 &= 55.30 \times 28.35 \text{ m} \\ &= 1567.76 \text{ say } 1568 \text{ m}^3/\text{s}.\end{aligned}$$

From Fig. 18 for

$$qH_3 = 1568$$

$$\text{Read } d_s = 27.7 \text{ m and } D_s = 106.00 \text{ m}$$

Compute d_s and D_s for the full range of spillway flows.

Determine maximum probable scour depth and corresponding distance from the spillway crest axis.

NOTE — As the discharge per metre width of bucket exceeds 45 m³/s confirmatory model tests are desirable (see 4.2.3).

ii) Bucket Radius

Assume lip angle of 45°

a) Using the formula,

$$\begin{aligned}\frac{R}{H_1} &= 8.26 \times 10^{-2} + 2.07 \times 10^{-3} F_D + 1.4 \\ &\quad \times 10^{-5} F_D^2\end{aligned}$$

$$\text{For } F_D = 52$$

$$\begin{aligned}\frac{R}{H_1} &= 8.26 \times 10^{-2} + 2.07 \times 10^{-3} \times 52 + \\ &\quad 1.4 \times 10^{-5} \times 52^2 = 0.228\end{aligned}$$

$$R = 0.228 \times 48.77 = 11.12 \text{ m}$$

b) From Fig. 8, for $F_1 = 4.55$

$$\text{Read } \frac{R}{d_1 + \frac{v_a^2}{2g}} = 0.4$$

$$\begin{aligned}R &= 0.4 \left(d_1 + \frac{v_a^2}{2g} \right) = 0.4 \left(2.47 + \frac{22.4^2}{2 \times 9.81} \right) \\ &= 11.22 \text{ m}\end{aligned}$$

Minimum bucket radius = 11.22 m

c) Using formula, $R = 0.305 \times 10P$

$$\begin{aligned}\text{where, } P &= \frac{v_t + 6.4H + 4.88}{3.6H + 19.5} \\ &= \frac{23.5 + 6.4 \times 11.2 + 4.88}{3.6 \times 11.2 + 19.5} = 1.675\end{aligned}$$

$$R = 0.305 \times 10^{1.675} = 14.43 \text{ m}$$

d) Using formula, $\sqrt{F_1} = 0.09 \frac{R}{d_1} + 1.96$

$$R = 4.75 \text{ m}$$

e) Using formula, $F_1 = 13R^{3/4} - 19.5$

$$4.55 = 13 \times R^{3/4} - 19.5$$

$$R = 11.71 \text{ m}$$

From (a), (b), (c), (d) and (e), adopt bucket radius $R = 12 \text{ m}$

$$H_1/R = 48.77/12 = 4.06$$

From Fig. 4, for $F_D = 52$, the range of H_1/R is 2 to 6

Thus the bucket radius of 12 m is acceptable.

ANNEX B
(Clause 4.2.2.2)

SOLID ROLLER BUCKETS (PROTOTYPE STRUCTURES)

Sl No.	Project	Head H_1 (m)	Discharge per Unit Length (q) $\text{m}^3/\text{s/m}$	Discharge Parameter $\frac{q}{\sqrt{g}H_1^{3/2}} \times 10^3$	Moperson and Karr's Range of H_1/R	Range of Radius R (m)	Actual R Provided (m)	As per Formula Suggested in IS	H_1/R as Provided	Lip Angle degrees
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
i)	Banas (Gujarat)	45.7	40.4	41.1	2 to 6	8.662–22.86	21.95	10.06	2.08	35°
ii)	Yeldari (Maharashtra)	40.5	53.6	65.3	2 to 6	6.77–20.77	21.34	10.36	1.9	35°
iii)	Siddeswar (Maharashtra)	31.9	26.6	49.6	2 to 6	5.33–16.00	15.14	7.01	2.11	40°
iv)	Kadana (Gujarat)	58.2	118	83.7	2 to 5	11.64–29.11	21.34	19.81	2.74	45°
v)	Linganamakki (Karnataka)	58	42.7	31.1	3 to 6	9.65–19.3	18.29	9.75	3.16	30°
vi)	Panam (Gujarat)	55	76.1	58.8	2 to 6	9.2–27.58	12	12.19	4.59	45°
vii)	Wolf Creek Kentucky (USA)	69.2	84.3	45.74	2 to 6	11.58–34.44	15.14	15.14	4.5	45°
viii)	Buggs Island, Virginia (USA)	50.9	65.5	57.58	2 to 6	8.53–25.45	12.19	11.28	4.18	45°
ix)	Centrehill, Fennesse (USA)	68.9	90.44	50.48	2 to 6	11.49–34.44	15.24	15.24	4.52	45°
x)	Charkhill, Georgia (USA)	56.4	89.60	67.51	2 to 6	9.45–28.19	15.24	14.32	3.70	45°
xi)	Greensboro, Carolina (USA)	17.15	12.73	54.6	2 to 6	3.66–10.97	5.18	3.96	4.579	45°
xii)	Headgate Rock, Arizona (USA)	25.3	46.48	116.5	2 to 5	5.06–12.65	12.19	12.50	1/0.480	45°
xiii)	Stewarts Ferry, Tennessee (USA)	37.3	56.42	79.38	2 to 5	7.44–18.59	12.19	12.50	1/0.388	45°
xiv)	Sakuma (Japan)	118.5	122.3	30.21	5 to 6	19.8–39.62	19.23	19.81	1/0.163	45°
xv)	Grand Coulee, Washington (USA)	128.4	56.33	12.32	6 to 7	18.29–22.34	15.24	16.15	1/0.119	45°
xvi)	Pennforest, Pennsylvania (USA)	40.4	27.89	81.1	2 to 5	8.08–20.19	5.18	13.41	1/0.128 5	45°
xvii)	Murdock (USA)	6.4	46.48	91.7	2 to 5	1.28–3.20	1.52	0.91	1/0.238	37°
xviii)	Malaprabha (Karnataka)	38.86	69.13	91.16	2 to 5	7.77–19.43	18.29	19.20	1/0.47	47°
xix)	Vaitarna (Maharashtra)	72.4	55.77	29.7	3 to 6	12.10–24.17	24.38	12.07	1/0.345	35°
xx)	Rihand (UP)	77.7	55.7	30.8	3 to 6	13.26–26.52	18.29	12.93	1/0.239	30°
xxi)	Nagarjunasagar (AP)	107.9	92	17.7	6 to 7	4.69–5.49	21.34	13.49	1/0.197 5	34°
xxii)	Gandhi Sagar (Rajasthan)	56.7	53.52	40.5	2 to 6	9.45–28.34	30.4	12.40	1/0.538	30°
xxiii)	Hirakud (Orissa)	39.4	104.1	135	2 to 5	7.92–19.69	150	19.7	1/0.387	40°
xxiv)	Guayabo (Central America)	54.6	119.9	68.02	2 to 5	10.36–27.43	10.95	15.23	1/0.20	59°

ANNEX C
(Clause 4.2.4)
SOLID ROLLER BUCKET PROTOTYPE DIMENSIONS

<i>Sl No.</i>	<i>Project</i>	<i>Country</i>	<i>Maximum Discharge Q</i> m ³ /s	<i>Maximum Discharge per m of Bucket Width q</i> m ³ /s/m	<i>Head from Maximum Reservoir Pool Elevation to Bucket Invert H_{1m}</i> m	<i>Bucket Radius R</i> m	<i>Bucket Lip Angle with Horizontal Ø</i> degree	<i>Tail Water Depth for Maximum Discharge</i> m
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
i)	Banas	Gujarat (India)	6 655	40.4	45.7		35	16.8
ii)	Damanganga	Gujarat (India)	22 048	115.37	50.0	17.00	40	24.0
iii)	Dharoi	Gujarat (India)	16 230	74.0	44.68	15.24	45	18.3
iv)	Kadana	Gujarat (India)	31 064	84.5	57.0	21.34	40	26.5
v)	Yeldari	Maharashtra (India)	10 478	53.6	40.5	21.34	35	19.2
vi)	Sidheswer	Maharashtra (India)	9 911	26.6	31.9	15.24	40	15.7
vii)	Buggs Islands	USA	21 804	65.5	50.9	12.19	45	21.3
viii)	Centre Hill	USA	12 914	90.4	68.9	15.24	45	26.3
ix)	Clark Hill	USA	29 959	89.6	56.4	15.24	45	21.1
x)	Davis	USA	5 437	72.6	54.0	22.86	45	21.3
xi)	Grand Coulee	USA	28 317	56.3	128.5	15.24	45	49.2
xii)	Head Gate Rock	USA	5 663	46.5	25.3	12.19	45	10.1
xiii)	Sterwarts Ferry	USA	5 642	56.4	37.2	12.19	45	18.4
xiv)	Wolf Creek	USA	15 150	84.3	69.2	15.24	45	31.3
xv)	Sakuma	Japan	9 798	122.2	118.6 ¹⁾	19.23	45	27.4

¹⁾ Spillway crest to bucket invert — H_2 .

ANNEX D
(Clause 4.3.2.5)

DESIGN OF SLOTTED ROLLER BUCKET — SAMPLE COMPUTATION

Given

Total discharge, Q = 1 815 m³/s
 Width of bucket = 41.67 m
 Maximum reservoir pool level = El 464.5 m
 Crest level of spillway = El 454.9 m
 Maximum tail water level = El 446.0 m
 H = maximum depth of overflow over the spillway crest
 = 464.5 – 454.9
 = 9.6 m
 H_3 = maximum reservoir pool level maximum tail water level
 = 464.5 – 446.0
 = 18.5 m
 v_t = $\sqrt{2g \times H_3} = \sqrt{2 \times 9.81 \times 18.5} = 19.05$ m/s

From Fig. 7 for

$$H = 9.6 \text{ m and } H_3 = 18.5 \text{ m}$$

$$\frac{v_a}{v_t} = 0.98$$

$$v_a = 0.98 \times 19.05 = 18.67 \text{ m/s}$$

$$\frac{v_a^2}{2g} = \frac{18.6^2}{2 \times 9.81} = 17.77 \text{ m}$$

q = discharge per metre width of bucket

$$= \frac{1815}{41.67} = 43.56 \text{ m}^3/\text{s}/\text{m}$$

$$d_1 = \frac{q}{v_a} = \frac{43.56}{18.67} = 2.33 \text{ m}$$

$$F_1 = \frac{v_a}{\sqrt{gd_1}} = \frac{18.67}{\sqrt{9.81 \times 2.33}} = 3.9$$

$$d_1 + \frac{v_a^2}{2g} = 2.33 + 17.77 = 20.10 \text{ m}$$

Use Fig. 8 with F_1 to find minimum allowable bucket radius

$$\text{For } F_1 = 3.9 \frac{R}{\left(d_1 + \frac{v_a^2}{2g}\right)} = 0.53$$

$$R = 0.53 \left(d_1 + \frac{v_a^2}{2g}\right)$$

$$= 0.53 \times 20.10$$

$$= 10.65 \text{ m}$$

$$R \text{ used} = 10.67 \text{ m}$$

$$\frac{R \text{ used}}{d_1 + \frac{v_a^2}{2g}} = 0.53$$

$$\text{with } \frac{R}{d_1 + \frac{v_a^2}{2g}} = 0.53, F_1 = 3.91 \text{ and using Fig. 9}$$

$$\frac{T_{\text{Min}}}{d_1} = 5.9$$

$$T_{\text{Min}} = 5.9 \times 2.33 = 13.75 \text{ m}$$

From Fig. 10, $T_{\text{Max}}/d_1 = 14.0$

$$T_{\text{Max}} = 14 \times 2.33 = 32.62 \text{ m}$$

Bucket invert is set at El 430.4 m giving T actual

$$= 446.0 - 430.4 = 15.6 \text{ m}$$

As against $T_{\text{Min}} = 13.75$ m, and

$$T_{\text{Max}} = 32.62 \text{ m}$$

From Fig. 12 adopt tooth spacing = 0.05 R

$$= 0.05 \times 10.67$$

$$= 0.534 \text{ m}$$

Tooth width = 0.125 R

$$= 0.125 \times 10.67$$

$$= 1.334 \text{ m}$$

Length of short apron = 0.5 R

$$= 0.5 \times 10.67$$

$$= 5.335 \text{ m}$$

Investigate for entire range of discharges.

ANNEX E
(Clause 4.3.4)

SLOTTED ROLLER BUCKET — PROTOTYPE DIMENSIONS

<i>Sl No.</i>	<i>Project</i>	<i>Country</i>	<i>Maximum Discharge Q</i>	<i>Maximum Discharge per m of Bucket Width q</i>	<i>Head from Maximum Reservoir Pool Elevation to Bucket Invert H₁</i>	<i>Bucket Radius R</i>	<i>Bucket Lip Angle with Horizontal Ø</i>	<i>Tail Water Depth for Maximum Discharge</i>
(1)	(2)	(3)	m ³ /s (4)	m ³ /s/m (5)	m (6)	m (7)	degree (8)	m (9)
i)	Ichari	India	10 600	160.0	42.50	12.00	45	25.0
ii)	Jawahar Sagar	India	21 238	95.2	45.4	15.24	45	22.3
iii)	Jayak Wadi	India	18 151	43.4	32.5	10.67	45	16.8
iv)	Poochampad	India	45 310	59.2	35.97	12.19	45	18.3
v)	Hasdeo Bango	India	21 660	108.3	82.2	21.0	45	37.28
vi)	Rajghat	India	33 892.9	99.10	48.82	16.5	45	26.95
vii)	Bansagar	India	43 380	106.92	68.93	17.6	45	28.10
viii)	Angostura	USA	7 844	95.5	48.2	12.19	45	22.6
ix)	Manheri	India	5 000	78.1	33.5	12.0	52	18.0
x)	Itiadoh	India	196.7	7.02	33.22	9.14	45	12.19
xi)	Karanjawan	India	1 620.0	21.24	40.58	6.00	45	12.3
xii)	Pench	India	12 000	50.63	37.00	13.0	45	21.6
xiii)	Ujjani	India	18 010	29.92	43.74	9.14	45	20.35
xiv)	Majalgaon	India	15 040	62.92	31.30	9.0	45	17.87

ANNEX F
(Clause 5.3)

TRAJECTORY BUCKET — PROTOTYPE DIMENSIONS

<i>Sl No.</i>	<i>Projects</i>	<i>Country</i>	<i>Maximum Discharge Q</i>	<i>Maximum Discharge per m of Bucket Width q</i>	<i>Head From Pool Elevation to Bucket Invert H_1</i>	<i>Bucket Radius R</i>	<i>Bucket Lip Angle with Horizontal ϕ</i>
(1)	(2)	(3)	m ³ /s (4)	m ³ /s/m (5)	m (6)	m (7)	degree (8)
i)	Banas	India	6 909	42.7	36.3	21.95	35
ii)	Gandhi Sagar	India	15 705	53.9	32.4	30.48	30
iii)	Girna	India	8 750	41.3	32.3	15.24	35
iv)	Hirakud	India	33 626	64.8	39.7	15.24	40
v)	Maithon	India	15 971	85.7	38.1	10.67	43
vi)	Mandira	India	8 496	42.7	19.8	7.62	NA
vii)	Panchet Hill	India	17 840	81.8	34.1	18.29	43
viii)	Ranapartap Sagar	India	21 238	61.1	31.4	16.76	40
ix)	Rihand	India	11 805	55.7	78.3	3.29	30
x)	Salandi	India	5 239	29.3	34.1	13.72	30
xi)	Sukhi	India	5 912	44.0	24.8	13.70	40
xii)	Tilaiya	India	3 851	24.7	29.0	6.1	30
xiii)	Ukai	India	35 963	97.6	47.9	27.43	40
xiv)	Vaitarna	India	5 663	27.9	70.7	24.38	35
xv)	Radhanagari	India	1 180	28.4	29.5	15.0	40
xvi)	Bhatsai	India	3 737	47.9	85.6	18.3	40
xvii)	Dimbhe	India	3 348	46.5	66.5	17.0	38
xviii)	Surya	India	3 180	44.2	48.2	13.5	45
xix)	Srirama Sagar	India	45 310	59.4	27.7	12.9	37
xx)	Anchor	USA	382	18.0	31.0	Parabolic	NA
xxi)	Arkport	USA	824	32.0	NA		45
xxii)	Chilhowee	USA	6 513	80.4	21.6	9.75	20
xxiii)	Conowingo	USA	24 919	36.3	27.9	12.19	12.5
xxiv)	Hartwell	USA	15 999	90.6	49.1	9.14	36.0
xxv)	Pineflat	USA	11 185	125.4	113.4	15.24	20.0
xxvi)	Safe Harbor	USA	27 467	34.0	17.8	12.80	27.0
xxvii)	Dnieprostroy	Russia	23 645	31.0	NA	11.55	NA
xxviii)	Bort	France	1 195	90.8	114.9	NA	NA
xxix)	Chastang	France	3 987	146.8	71.0	NA	NA
xxx)	Genissiat	France	2 690	179.8	64.0	NA	NA
xxxi)	L'Aigle	France	3 987	124.7	89.9	NA	NA
xxxii)	Maregos	France	1 393	26.9	77.1	NA	NA
xxxiii)	St.Etiennna Centales	France	714	70.0	71.1	NA	NA
xxxiv)	Castelodo Bode	Portugal	13 998	249.9	112.8	NA	NA
xxxv)	Pictoe	Portugal	NA	NA	90.8	NA	NA
xxxvi)	Clereland	British Columbia	1 226	50.2	91.4	NA	NA
xxxvii)	Kamishiiba	Japan	2 152	55.7	110.0	NA	NA

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